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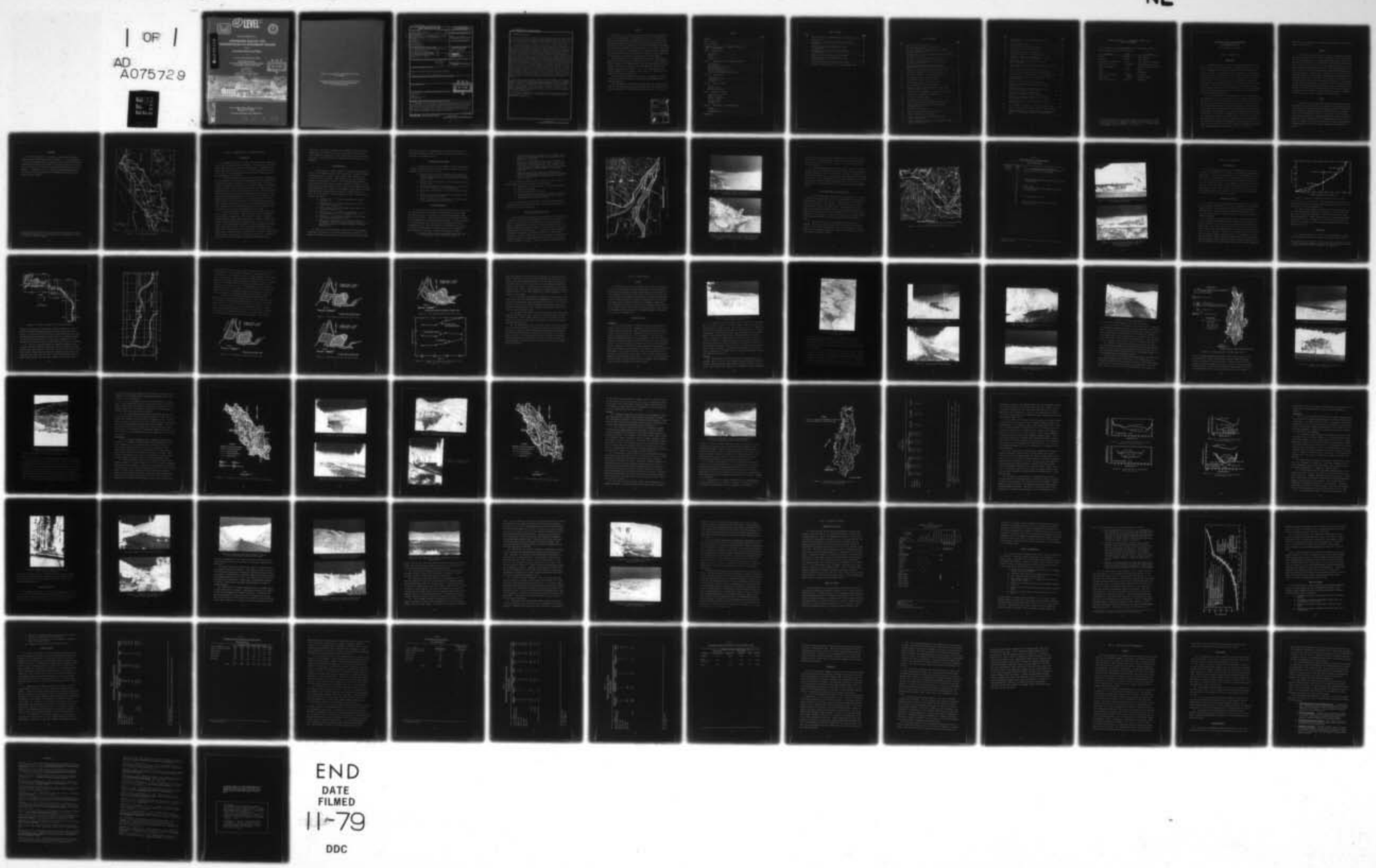

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ENGINEERING GEOLOGY AND GEOMORPHOLOGY OF STREAMBANK EROSION

Report I

EEL RIVER BASIN, CALIFORNIA

by

Lawson M. Smith and David M. Patrick

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Streambank erosion, including other fluvial modifications, has occurred in the delta region of the Eel River in Humboldt County, California. Two streambank erosion control demonstration sites have been proposed in order to alleviate the loss of property and to evaluate new techniques for bank protection. The purpose of this report was to analyze, describe, and document the factors and causes of streambank erosion in the Eel River delta.

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CONT

The Eel River Basin occupies an area of 3625 square miles and has a length of 120 miles from the river's source on Bald Mountain in Mendocino County to its mouth in the delta region of Humboldt County. With the exception of the delta, all of the basin lies in the rugged and steep coastal ranges of California.

Erosional phenomena in the delta were studied by considering site and nonsite (basin) factors and by utilizing historical topographic map coverages, aerial infrared photography, published and unpublished reports, and field visits. The study of site factors (bank materials, longitudinal profiles, and meander configurations) indicated that the granular bank material was easily erodible; that the delta region was receiving an exceptionally large influx of river sediment, resulting in an increase in channel elevation; and that between 1940 and 1972 the lower 5 miles of channel had experienced a gradual increase in area of 23 percent and island area had increased by 67 percent. Bank erosion in the delta was considered to be triggered by the mechanism of channel widening; the widening was the response of the stream to certain atypical climatic events. Of particular significance was the 1964 flood, which had a return frequency greater than 100 yr and sent river stages as much as 15 ft higher than previous record stages. At one location, a 37-day sediment discharge was computed at 116 million tons, whereas the previous 8-yr total was only 94 million tons. Generally, the evidence from the study of site factors and conditions indicated that the causes of bank erosion in the delta were not site related (that is, there were no conditions of climate nor of man's activities operating in the delta itself that were directly causing the changes in fluvial regime). Therefore, erosion must be caused by the impact of climatic conditions or by the interrelationship between climate and other conditions/activities within the basin (nonsite factors).

These nonsite factors, which include geology, topography, vegetation, and land use, were reviewed and studied in terms of their contribution to sediment production ~~and their interrelationship with climate.~~ The natural environmental conditions present in the basin were found to be conducive to high sediment yields. The conditions included steep slopes, high relief, thin soil cover, and steeply dipping, folded and fractured bedrock. Land use activities, such as grazing, timber harvesting, and road building, were also found to be contributors of high sediment yields.

The causes of bank erosion in the delta are believed to be due to the influence of man's activities in an environment that is already predisposed to high sediment production.

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PREFACE

This report is the first of a series dealing with the engineering geology and geomorphology of streambank erosion. The study was conducted in the Geotechnical Laboratory (GL) of the U. S. Army Engineer Waterways Experiment Station (WES) and was funded by the Office, Chief of Engineers (OCE), by authority of the Section 32 Program, "Streambank Erosion Control, Evaluation, and Demonstration Act of 1974." This study was a part of Task II, "The Influences of Fluvial Geology on Streambank Erosion," which was a part of Work Unit 4, "Research on Soil Stability and Identification of Causes of Bank Erosion," of the Program.

The investigation was performed during the period June 1977 to August 1978 under the general supervision of Mr. J. P. Sale, Chief, GL; Dr. D. C. Banks, Chief, Engineering Geology and Rock Mechanics Division (EGRMD); and Mr. C. L. McAnear, Chief, Soil Mechanics Division, and Principal Investigator, Work Unit 4. Mr. L. M. Smith and Dr. D. M. Patrick, EGRMD, were the authors of this report. Dr. Patrick was the Principal Investigator of Task II.

This report was reviewed by Dr. Charles S. Alexander, University of Illinois, the South Pacific Division, CE; and by members of the Steering Committee.

The Commanders and Directors of the WES during the conduct of the study and the preparation of this report were COL J. L. Cannon, CE, and COL N. P. Conover, CE. The Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
acres	4046.856	square metres
acre-feet	1233.482	cubic metres
acre-feet per square mile	47.625	cubic metres per kilometre
cubic feet per second	0.02831685	cubic metres per second
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
inches	25.4	millimetres
miles (U. S. statute)	1.609344	kilometres
square miles	2.589988	square kilometres
tons (2000 lb, mass)	907.1847	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

ENGINEERING GEOLOGY AND GEOMORPHOLOGY
OF STREAMBANK EROSION

EEL RIVER BASIN, CALIFORNIA

PART I: INTRODUCTION

Background

1. Streambank erosion is actively removing valuable land in the lower portions of the Eel River Basin in norther California. The erosion of streambanks is a complex environmental process that may be caused by a number of interrelated factors pertaining to the nature of the erosion site (site factors) and to processes in effect considerable distances from the site (nonsite factors). Generally stated, streambank erosion at a particular site may be influenced by a phenomenon occurring practically anywhere within the drainage basin of the stream in question. These site and nonsite factors include natural causes, such as climate, vegetation, soil characteristics, geology, and geomorphology, and man-induced factors, such as channel and drainage modification and removal of vegetation.

2. In accordance with the Streambank Erosion Control Evaluation and Demonstration Act of 1974 (Section 32), two demonstration sites have been proposed on the Eel River and the Van Duzen River (tributary to the Eel) for the development and monitoring of erosion control structures. The Eel River Basin generally and the streambank erosion demonstration sites specifically afford the geotechnical engineer and environmental planner an excellent example of the complex interrelationship of factors stated above. The type of streambank erosion discussed in this report, i.e. man-induced, occurs in the lower portion of the Eel River Basin (Eel River delta) in an area that, although settled and cultivated, does not exhibit the characteristics capable of initiating significant erosion. Thus the causes of erosion are operating throughout the drainage basin and mainly many miles upstream of the sites of interest.

Therefore, the integration of site and nonsite factors is one important aspect of this report.

Purpose

3. The primary purpose of this study was to determine, describe, and analyze the factors contributing to streambank erosion in the delta area of the Eel River Basin. The secondary purpose was to present and demonstrate the application of techniques and methodologies that may be used to determine causes of erosion. This regional study was a part of broader geological investigations devoted to determining causes of bank erosion and the influence of engineering geology and geomorphology on stream instability. Selected sites or areas such as the Eel River Basin have been studied for the purpose of demonstrating these causal relationships and geological influences. The concepts, considerations, and methodologies presented herein are generally applicable to other sites in other regions. Furthermore, the authors believe that the geological analyses and considerations presented provide useful information on the nature of the fluvial environment and should, therefore, be included (in greater or lesser detail) in the evaluation or design of hydraulic structures and in the overall analysis of fluvial systems.

Scope

4. Data used in this study were obtained from published reports, topographic maps, aerial infrared photography, field observations, and interviews with individuals having firsthand knowledge of the Eel River. For the most part, published sources of information did not address erosion at the demonstration sites in the delta per se but pertained to hydrologic and erosional phenomena throughout the basin. This report represents a brief synthesis of several comprehensive studies of the basin, an analysis of these data with respect to their significance to the demonstration sites, and a general evaluation of the causes of erosion.

Location

5. The Eel River Basin is located in northwestern California, draining an area of 3625 square miles* (Figure 1). From its headwaters on the slopes of Bald Mountain in Mendocino County, the Eel flows south through Lake Pillsbury, west through Van Arsdale Reservoir, and northwest to its mouth on the Pacific, approximately 280 miles north of San Francisco. Averaging 30 miles in width and having a maximum length of 120 miles, the Basin occupies parts of Humboldt, Trinity, Mendocino, Glenn, and Lake Counties.

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* A table for converting U. S. customary units of measurement to metric (SI) units is given on page 6.

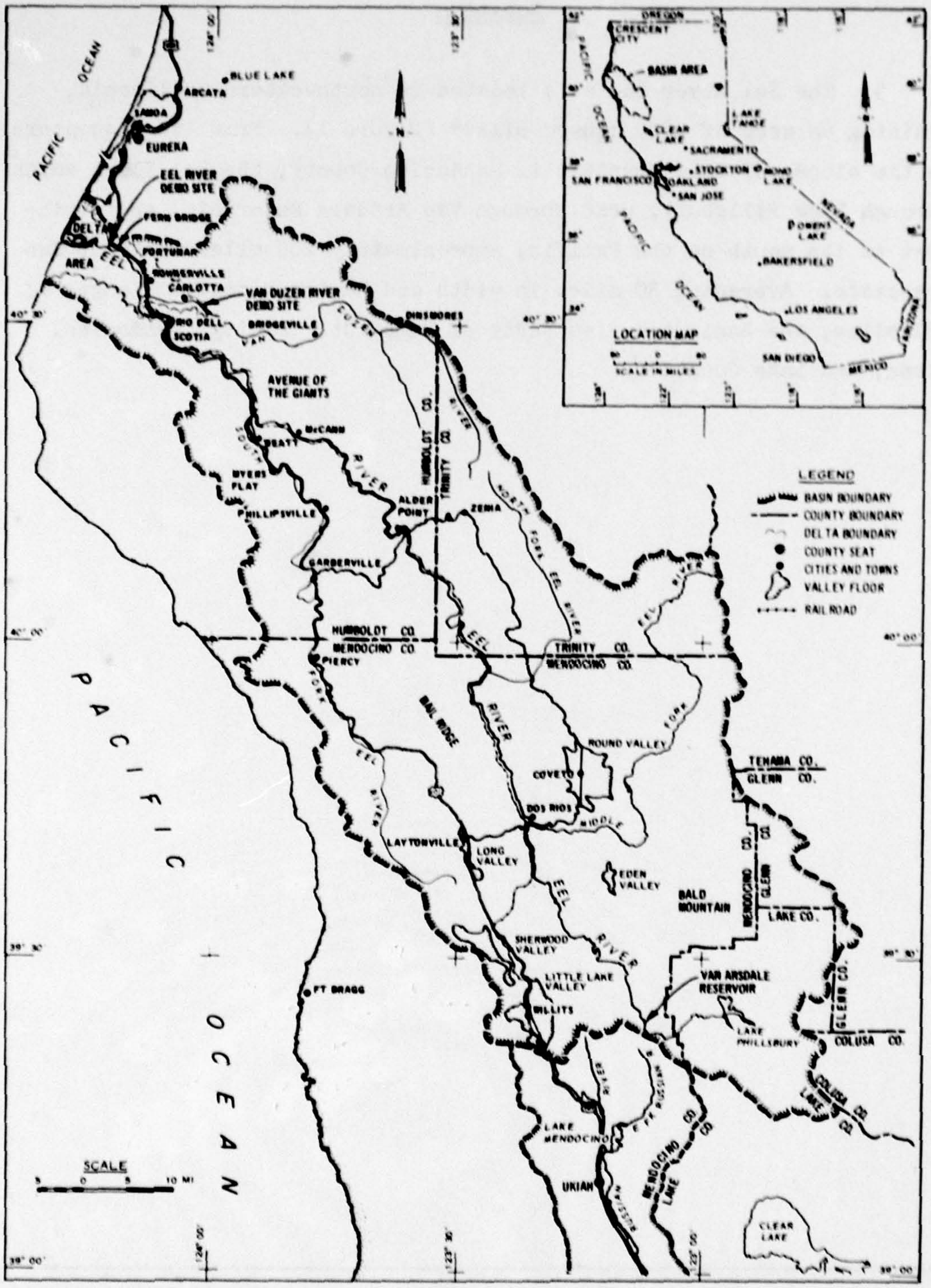


Figure 1. Eel River Basin, California

PART II: CHARACTERISTICS OF STREAMBANK EROSION

Introduction

6. Streambank erosion is a natural geomorphic process, working at various rates along the courses of streams. In some reaches, this rate may be imperceptible; in others, relatively rapid. Streambank erosion is dependent upon two basic factors: available energy and bank resistance. Both factors are highly variable in natural occurrence and can be significantly altered by man.

7. Available energy at a given point along a stream is dependent upon the conversion of potential energy arising from two different water elevations into kinetic energy due to the flowing water. The kinetic energy is dissipated in friction at the channel boundaries. The kinetic energy available to erode the sides and bottom of the channel can be measured in terms of the velocity and volume of flow. The interrelationship between potential and kinetic energy and velocity is more or less defined by the channel gradient and cross section. The volume of flow depends upon the characteristics of the drainage basin and climate. Bank resistance involves the ability of the channel materials to withstand the shear stresses that are developed at the water-channel interface. Ordinarily, finer grained materials such as clay exhibit greater resistance to erosion than coarser materials such as sand.

8. Erosion produced by a stream may occur along the channel bed and/or channel sides (banks). Where the erosion occurs is dependent upon the type of stream, that is, "youthful" or lower order (small) streams generally exhibit bed eorsion, whereas "mature" or higher order (large) streams primarily exhibit bank erosion. In either case, there usually is a balance between the material eroded and material deposited along a particular stretch. Thus, the migration of meander loops on large, mature streams is merely the consequence of the interaction between erosion, transportation, and deposition. The extent to which stream erosion poses a serious hazard in terms of property loss is dependent upon the rate of erosion and/or the balance between erosion and

deposition. The study of stream erosion problems should include the identification of potential causes of increased erosion rates and/or erosion-deposition imbalances. These causes may be influenced by site and nonsite conditions and may be explained by the principles of river mechanics.

River Mechanics

9. The analysis of fluvial systems is based upon the consideration of certain quantities that define the system: discharge, sediment discharge, grain size, depth of flow, channel width, channel slope, valley slope, and sinuousity. These quantities are both hydrologic/hydraulic and geomorphic in nature. The interrelationship between these variables is based upon a concept of dynamic equilibrium. Investigations by Leopold and Maddock (1953), Lane (1955), Schumm (1971), and Santos-Cayudo and Simons (1972) have determined several general relationships among hydrologic-geomorphic variables of streams that are of great use in the analysis of stream channel activity. These relationships are as follows:

a. Depth of flow Y is directly proportional to water discharge Q.

b. Channel width W is directly proportional to both Q and sediment discharge Q_s.

c. Channel shape, expressed as width to depth ratio W/Y is directly related to Q_s.

d. Channel slope S is inversely proportional to Q and directly proportional to Q_s and grain size D_{50}.

e. Sinuosity s is directly proportional to valley slope and inversely proportional to Q_s.

f. Transport of bed material Q_s is directly related to stream power T_O^V and concentration of fine material C_F, and inversely related to the fall diameter of the bed material D_{50}.

10. Based on these relationships, stream activity and geomorphic change may be estimated by incorporating quantitative estimates of the hydrologic variables into equations of proportionality between variables.

Knowledge of how a basin characteristic or activity influences the hydrologic-geomorphic variables may help to explain the occurrence and magnitude of streambank erosion.

Streambank Erosion Types

11. The American Society of Civil Engineers (ASCE) Task Committee on Channel Stabilization Works and others have described six types of streambank erosion (Keown et al. 1977):

- a. Attack at the toe of the underwater slope, leading to bank failure and erosion. The period of greatest bank failure normally occurs in a falling river at the medium stage or lower.
- b. Erosion of soil (bank material) along the bank caused by current action.
- c. Sloughing of saturated cohesive banks, i.e. banks incapable of free drainage, due to rapid drawdown.
- d. Flow slides (liquefaction) in saturated silty and sandy soil.
- e. Erosion of the soil by seepage out of the bank at relatively low channel velocities.
- f. Erosion of upper bank, river bottom, or both due to wave action caused by wind or passing boats.

Erosion Mechanisms

12. The ASCE erosion types described above provide an insight into the problem that would be useful for design; however, in some cases, this classification is not helpful in relating the phenomenon (bank erosion) to its cause. Ideally, the cause should be related or linked to the phenomenon by a geomorphological mechanism. From the standpoint of fluvial geomorphology, there are three mechanisms that produce streambank erosion. These mechanisms are interdependent and are controlled by the semiquantitative relationships given in paragraph 9. The mechanisms are widening, deepening, and sinuosity changes.

- a. Widening involves channel enlargement caused by either or both increased flow and sediment discharges (see

relationships b and c, paragraph 10). If sediment discharges are large, widening may be accompanied by channel aggradation or infilling.

b. Deepening is the degradation or scouring of the channel bottom; this leads to bank instability or sloughing due to removal of lower bank material. The scouring of the lower portion of the channel may be affected by increased flows (paragraph 9a) and/or changes in slope (paragraph 9d).

c. Sinuosity change produces bank loss during and upon change in stream meander configuration; however, the bank loss is usually accompanied by bank accretion along the affected stretch.

13. The causes of bank erosion at a particular site or stretch must be analyzed in terms of several factors, namely:

a. Characteristics of the erosion, e.g., ASCE erosion type.

b. Geomorphic mechanisms.

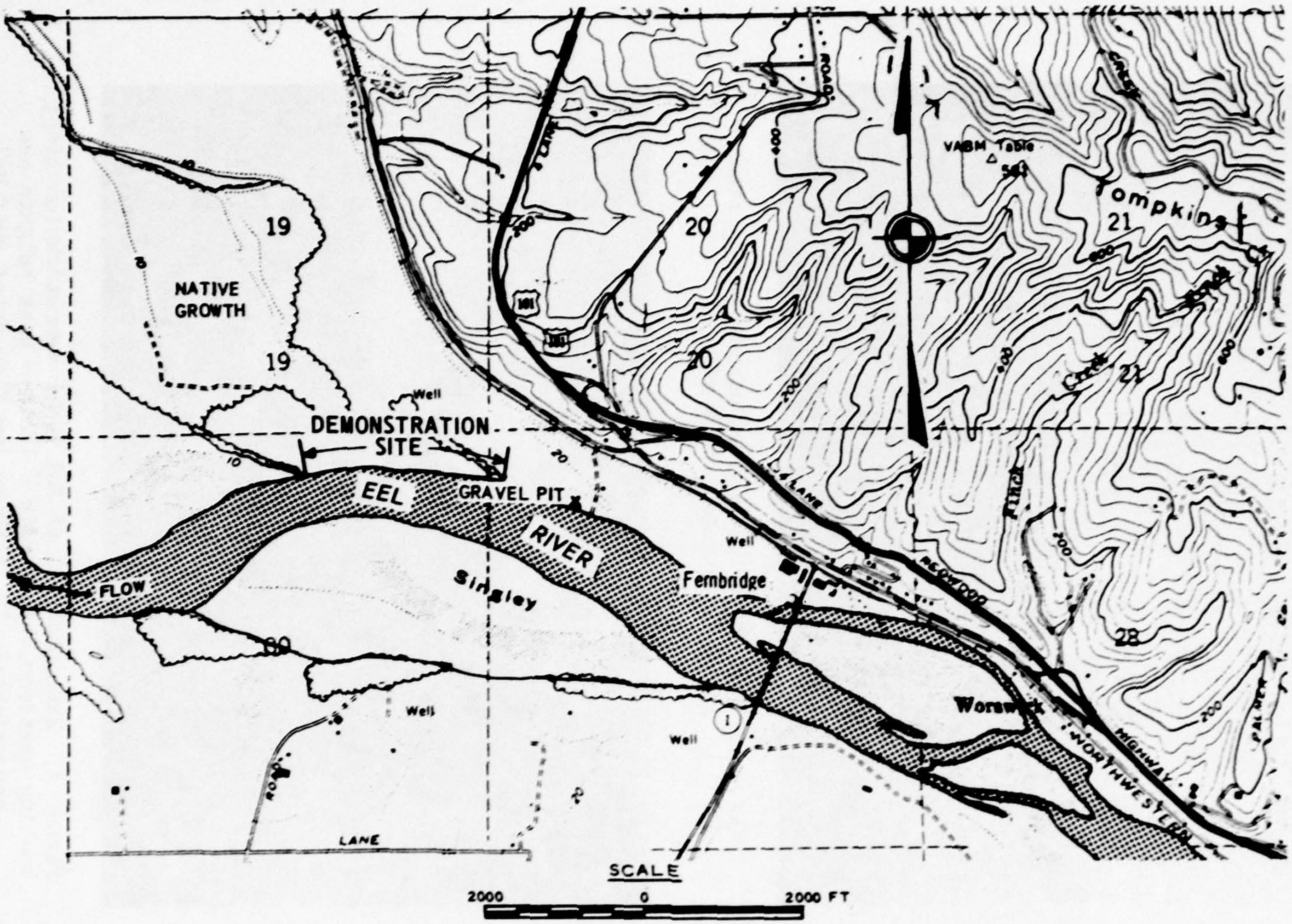
c. Hydraulic-geomorphic variables.

d. The integration of a, b, and c with respect to conditions at the site or stretch in consideration (site factors) and beyond the site (nonsite factors).

14. The remaining sections of Part II will describe the general characteristics of the two sites. Parts III and IV will address site and nonsite factors, respectively.

Eel River Demonstration Site

15. The Eel River demonstration site (Figure 2) is located on the north bank of the Eel River approximately 6 miles upstream from the mouth, 2.5 miles northwest of Fortuna, and 14.5 miles southeast of Eureka. Drainage area at this point is about 3600 square miles. At bank-full stage, the channel is about 0.5 mile wide with a capacity of approximately 150,000 cfs (Figure 3). Flows at this point have been estimated to vary between 100,000 and 840,000 cfs. Bank heights observed at low stages range from 8 to 12 ft and consist of sandy silts on gravels (Figure 4). Bank materials at both the Eel and Van Duzen sites are similar in nature. A layer of overlying coarser material,



(Courtesy USAE District, San Francisco, March 1977)

Figure 2. Eel River demonstration site location

Figure 3. Eel River channel at demonstration site; looking upstream, river mile 6

Figure 4. Bank material at Eel River demonstration site; looking upstream, river mile 6 (Note: Bank heights are approximately 15 ft above low flow water surface)

probably deposited during a period of high water, could be seen in the banks of finer alluvial deposits. Bank slopes are nearly vertical for the upper 60 percent and about 1 vertical on 1.5 horizontal for the lower talus portion.

16. Rapid streambank erosion is occurring at the site. Located on the outside of a meander with a radius of about 1 mile, the bank has retreated approximately 600 ft since 1968. The site is situated in the Eel River alluvial valley (or delta), which has experienced much meandering in recent times. Streambank erosion is quite extensive in this area with the loss of much valuable agricultural land. The alluvial silts and gravels in the bank materials offer little resistance to streambank erosion.

Van Duzen River Demonstration Site

17. The Van Duzen River demonstration site (Figure 5) is situated on the north bank approximately 8 miles upstream from the confluence of the Van Duzen with the Eel. The site is about 2 miles east of Carlotta and 20 miles northwest of Bridgeville. The Van Duzen at this point drains an area of about 280 square miles. Average bank-full width is about 1000 ft with an estimated capacity of approximately 30,000 cfs. Minimum flow is about 10 cfs with a maximum of 54,000 cfs. Bank heights range from 7 to 10 ft and are composed of sandy silts on gravel (Table 1). Bank slopes were similar to those at the Eel River Site (Figures 6 and 7).

18. The Van Duzen site is also situated on the outside of a meander. The alluvial bank materials are easily eroded, and lateral erosion of 1100 ft has occurred since 1959. Similar activity is prevalent in both upstream and downstream directions, causing loss of agricultural and residential property.

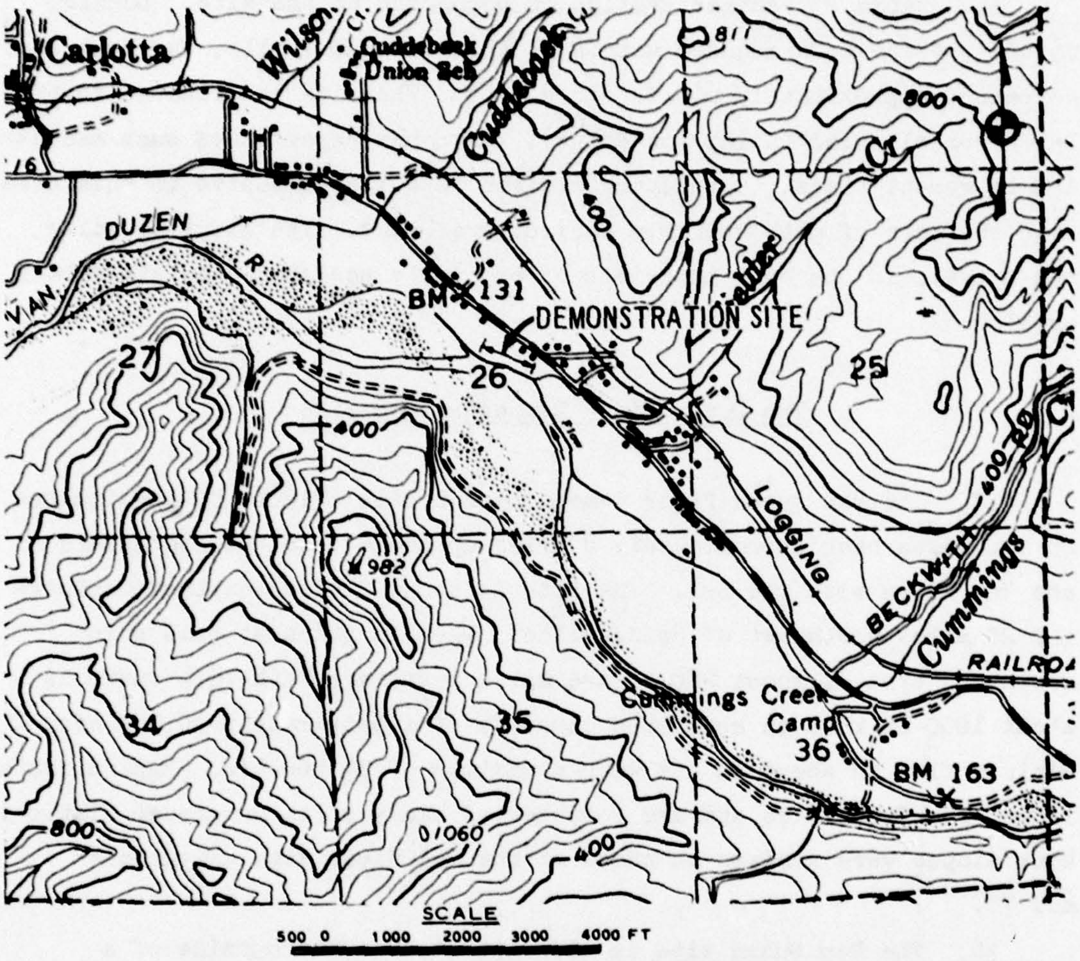


Figure 5. Van Duzen River demonstration site location

Table 1

Boring Log (2F-1) of Bank Material
at Van Duzen Site

Elevation ft msl*	Depth ft	Description of Bank Material
133.9	0	Silt; gray, soft, moist; some sand
	1	
	2	
	3	
	4	
	5	Silty, gravelly, sand; moist; loose; 4-in. (max)
	6	rounded gravel
	7	
	8	
	9	∇ Water table
	10	Silty, sandy, gravel; wet; dense; 5-in. (max)
	11	rounded gravel
	12	
	13	
	14	
	15	6-in. sand layer at 15 ft
	16	
	17	
	18	Sandy silt; tan, damp, firm; some gravel
	19	Bottom at 19 ft

* Mean sea level.

Figure 6. Van Duzen River demonstration site bank slope; left bank, river mile 8

Figure 7. Bank and channel material at Van Duzen River demonstration site; right bank, river mile 8

PART III: SITE FACTORS

Bank Material

19. Several characteristics of the demonstration sites strongly influence the erodibility of the banks. Of considerable importance is bank material. Both of the demonstration sites have banks composed of sandy silts on gravels typical of alluvial valleys (see Figures 4 and 7). This material apparently has a very low resistance to erosion; hence, a low critical tractive force (drawing or pulling action of the flow) will erode the banks. Both sites are located on the outside of large meanders where tractive force is greatest for all flows except flood flows; however, it is possible for tractive force to exceed the critical tractive force during flood flows.

Longitudinal Profile

20. Channel slope is a hydrologic variable related to flow, sediment discharge, and sediment size. Slope is determined from the longitudinal profile. The longitudinal profile may thus yield important information about channel slope both upstream and downstream of the site, and in some instances, may provide data on historical changes in channel morphology.

21. Therefore, the longitudinal profile of the Eel River from its mouth to a point approximately 85 miles upstream was plotted from most recent (1966-1972) 1:24,000 scale U. S. Geological Survey (USGS) topographic maps. The longitudinal profile was also plotted from earlier 1:62,500 scale USGS topographic maps from the mouth to a point approximately 135 miles upstream. These two plots permitted historical comparison to be made of channel characteristics. The examination of these profiles shown in Figure 8 generally suggests that within the two periods of observation there had been considerable channel degradation 40 to 50 miles upstream of the demonstration site and that channel aggradation

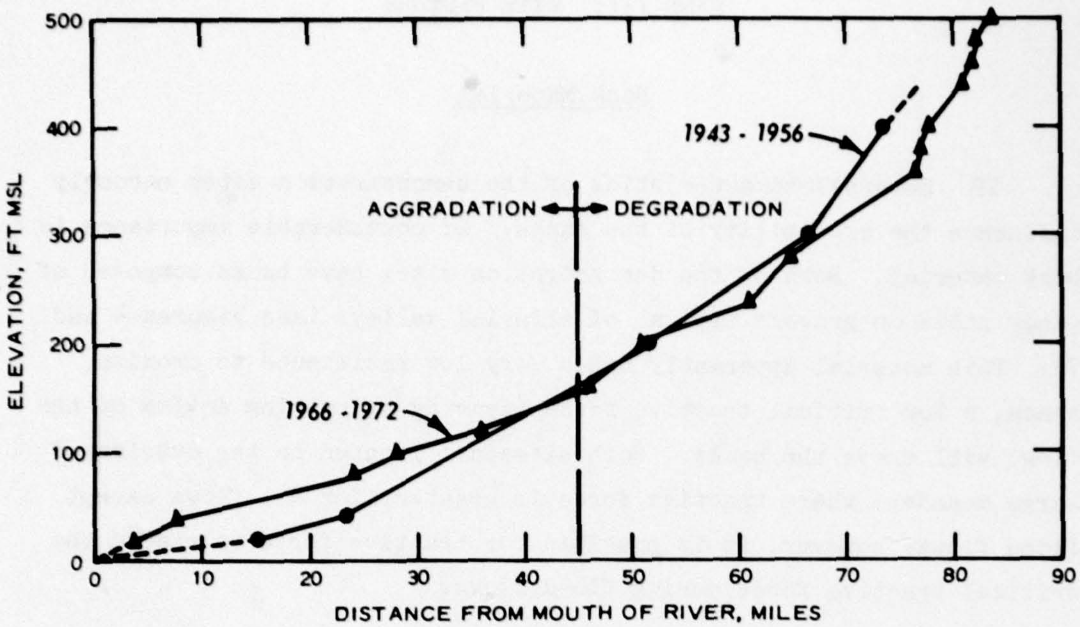


Figure 8. Changes in longitudinal profiles of the Eel River

had occurred at or near the site.* These phenomena are presumed to be related to the flows and sediment discharges associated with the 1964 and earlier floods (see paragraph 49).

22. These floods produced considerable hillside and channel erosion upstream at higher elevations in the basin. The resultant sediments were transported downstream to the Eel River delta area where they were deposited. Channel deepening was thus controlled downstream by base level control. Probably if it were not for this nearness to base level, the channel would have degraded downstream near the demonstration sites also.

Meandering

23. The low resistance to erosion of the streambanks is evident in the meandering nature of the channels in Figures 9 and 10. Both

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* Similar historical changes in channel slope can also be seen on longitudinal profiles of the Van Duzen River (see Figure 48).

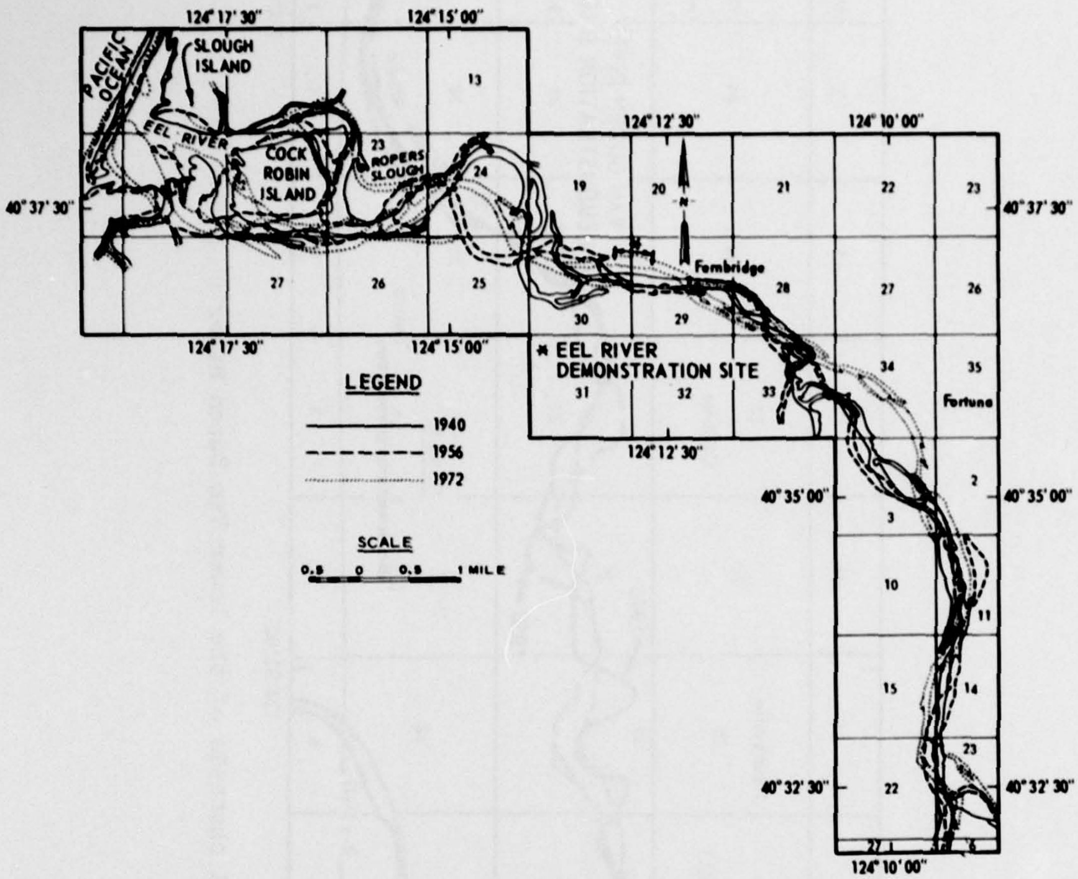


Figure 9. Historical channels of the lower Eel River

channels have experienced substantial horizontal migration in the 19- and 14-yr intervals between 1940 and 1959 and 1959 and 1973, respectively. The north bank of the Eel River at the demonstration site near Fernbridge has moved approximately 600 ft and 900 ft northward between 1940 and 1959 and 1959 and 1973, respectively. Meandering of other reaches in the lower Eel varies in horizontal extent from 250 to 5600 ft.

24. In order to further analyze the meander configuration and to identify historical changes that may have occurred, channel and island surface areas were measured in the lower 5 miles of the Eel River in the delta region. These data were taken from topographic map coverage for the years 1940, 1951, 1959, and 1972. Channel area included the total bank-to-bank channel area (including islands) for the 5-mile reach.

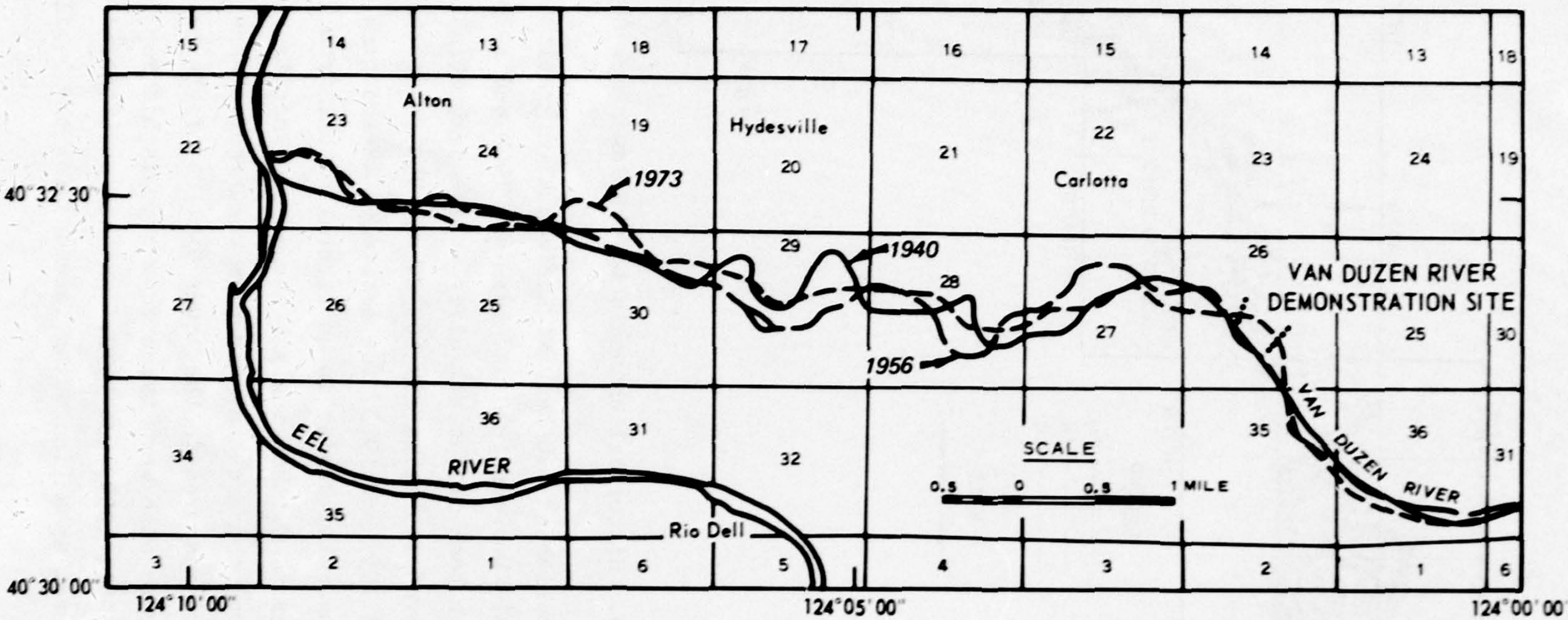


Figure 10. Historical channels of the lower Van Duzen River

Island area was the total areal extent of channel islands in the reach. The usefulness of these surface measurements is dependent upon the identification of the bank-full channel from the topographic maps regardless of stream stage. Along relatively straight stretches and at the outside of bends, the bank-full channel can usually be easily recognized; however, some judgment must be exercised in identifying the channel boundary on the inside of bends. The measurement of island areas poses similar problems, and these data should be considered to be approximate. Figures 11-14 show the meander patterns for the 4 years of coverage. Plots of channel and island areas versus time are shown in Figure 15.

25. The area versus time plots reveal that there has been a general increase in both total channel area and island area since 1940. The increase in areas between 1940 and 1974 was 23 percent for channel and 67 percent for island. Further examination of the plots in Figure 15 indicates that the trends, especially with respect to channel area, increase rather abruptly after 1952. Note that the true channel area (that is, the difference between the total channel area and the total island area) has remained relatively unchanged. This indicates

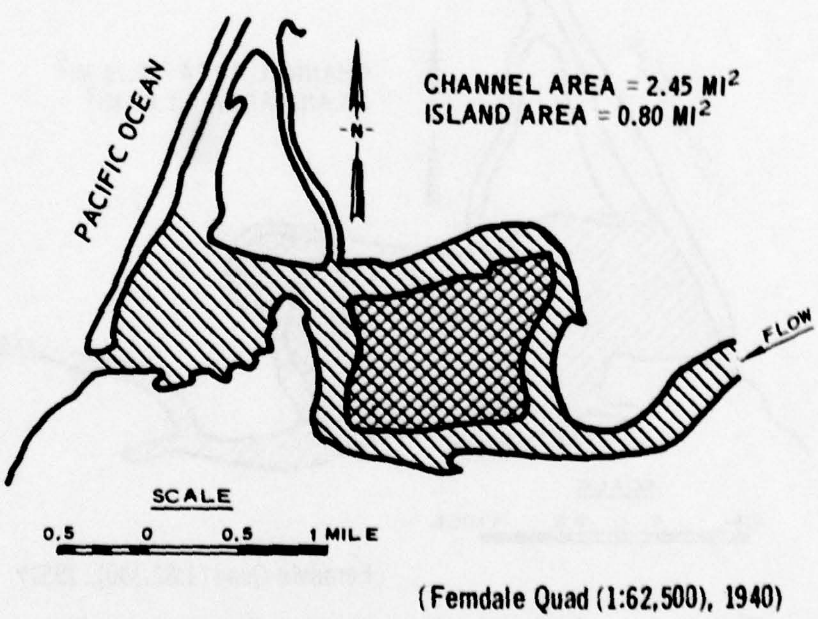


Figure 11. 1940 meander pattern, Eel River delta

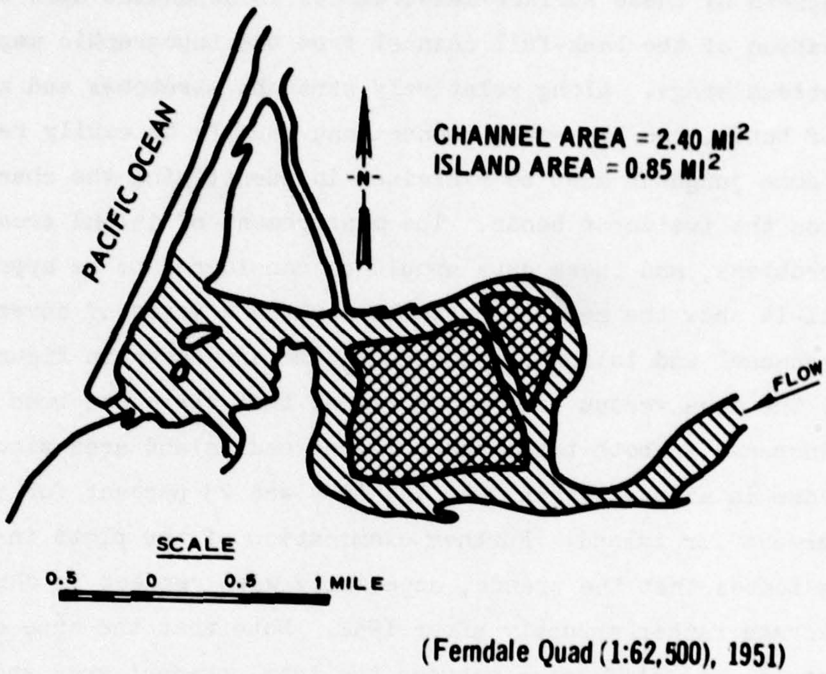


Figure 12. 1951 meander pattern, Eel River delta

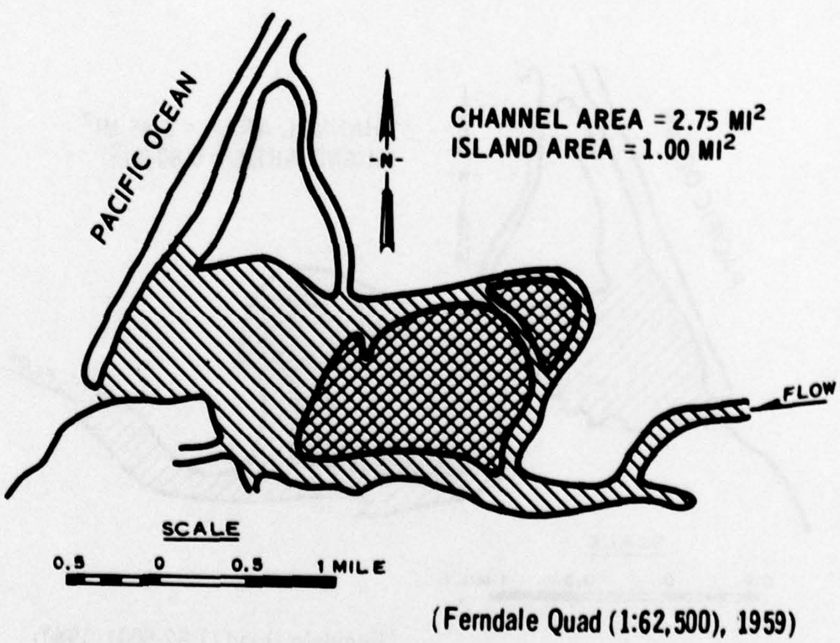


Figure 13. 1959 meander pattern, Eel River delta

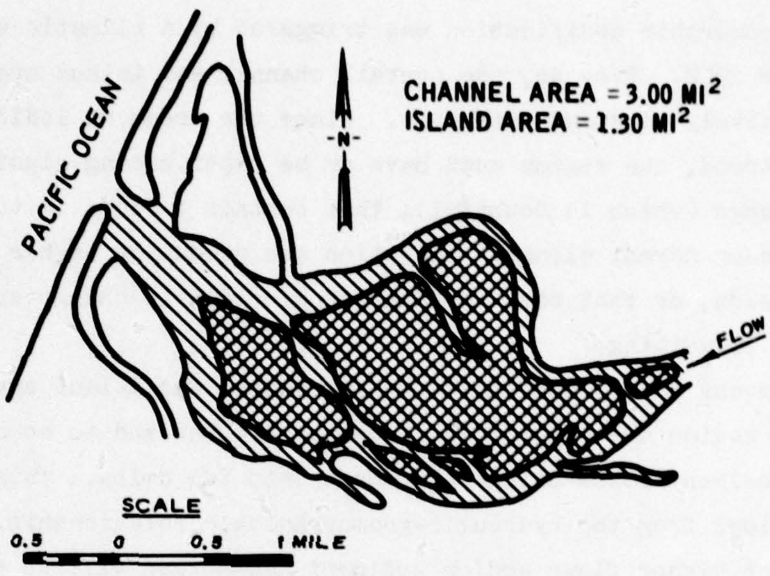


Figure 14. 1972 meander pattern, Eel River delta

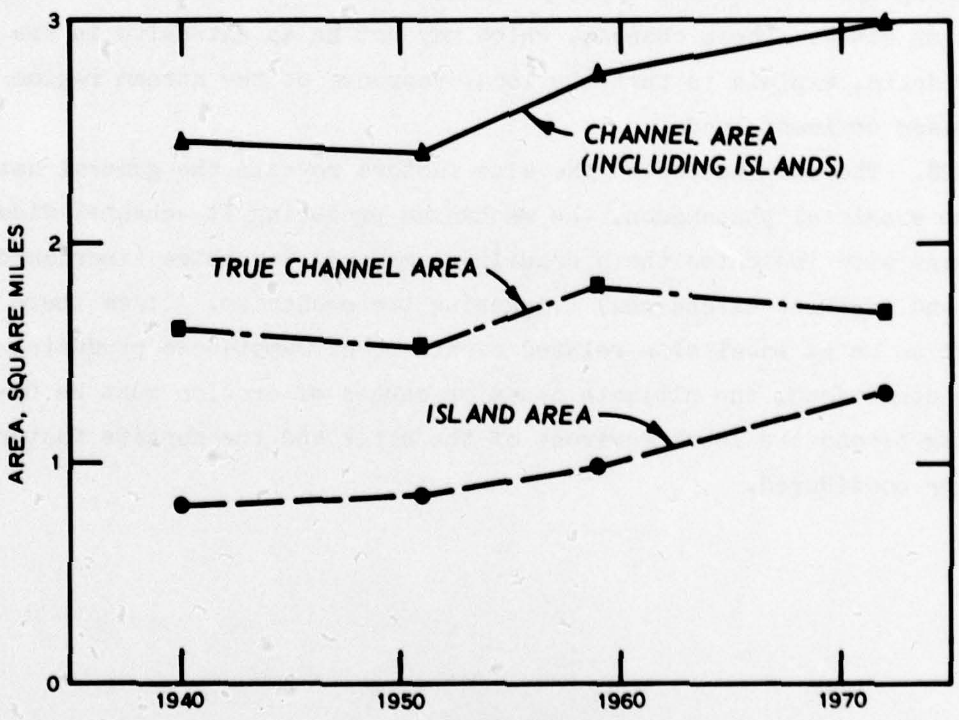


Figure 15. Changes in channel and island areas in the lower 5 miles of the Eel River

that this geomorphic modification was triggered by a climatic event or events after 1952. Even so, the overall channel and island areas would remain relatively constant with time. Since the areas do indicate an increasing trend, the region must have or be experiencing significant climatic change (which is doubtful); that certain factors in the basin operating under normal climatic variation are producing higher flows and sediment yields; or that some combination of climatic change and "other factors" is prevailing.

26. In any event, the increases in channel and island areas in the lower delta region are considered to be significant and to be caused by increased sediment loads being introduced into the delta. This increase in area follows from the hydraulic-geomorphologic relationship, which predicts that higher flows and/or sediment discharges will be accompanied by increased channel widths.

27. The changes detected in the lower delta are, most likely, also occurring upstream in the upper portions of the delta and at the demonstration sites. These changes, which may not be as extensive in the upper delta, explain in part the local response of the stream regime to increased sediment loads.

28. The examination of the site factors reveals the general nature of the erosional phenomenon, the mechanism producing it--channel widening--and also indicates the hydraulic-geomorphic variables (increased flow and sediment discharges) triggering the mechanism. Since there appear to be no local site-related events or circumstances producing these conditions, the ultimate cause or causes of erosion must be operating beyond the local environs of the sites and the nonsite factors must be considered.

PART IV: NONSITE FACTORS

General

29. This part of the report describes and relates the conditions, events, and circumstances in the Eel River Basin that are believed to be affecting the overall hydrologic regime and are contributing to geomorphic change in the delta. These nonsite factors are all operating upstream of the sites and may be categorized as either natural or man-induced. Natural factors are inherent characteristics of the natural environment such as climate, geology, and topography. Man-induced factors involve alterations of the natural environment by man and may include such activities as removal of natural vegetative cover (logging and overgrazing) and interruption of streamflow regimes (construction of reservoirs, realignment, etc.).

Natural Factors

Topography

30. The Eel River Basin is contained almost entirely within the coastal ranges of California. Topography consists of a series of northwest-southeast trending ridges and canyons reflecting a complex geologic history (Figure 16). Elevations range from sea level at its mouth to approximately 7500 ft at its headwaters. The Eel and its tributaries generally parallel the predominant trend of the ridge and canyons, breaching the ridges on occasion (Figure 17). This structural control of the stream courses has resulted in a trellis-like drainage pattern. Streams of the Eel River Basin descend from the uplands in deep, narrow canyons with relatively steep gradients (Figures 18 and 19). Development of an extensive alluvial valley with associated fluvial features is restricted to only a small reach of the Eel River approximately 10 miles upstream from its delta. It is in this relatively small alluvial valley, in which the Eel is free to meander, that streambank erosion is most pronounced in horizontal extent.

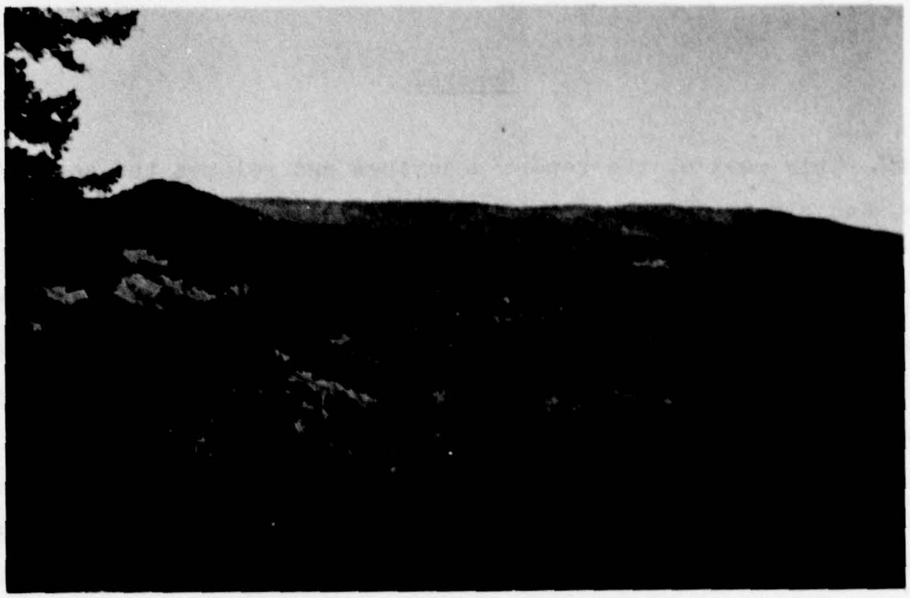


Figure 16. Eel River Basin topography, 4 miles north of Zenia

31. A major contribution to high erosion potential is topography. Much of the basin consists of mountain slopes. These slopes vary tremendously but are commonly quite steep (Figures 20 and 21). Many slopes are delicately adjusted to slope material and may fail at the slightest interruption. Steep mountain slopes play an important role in streambank erosion along the lower reaches of the Eel above its alluvial valley. Unlike most drainage basins, the valley of these reaches becomes more narrow in a downstream direction, causing restriction of flow with increased velocities and high erosion potential (Figure 22). An additional topographic factor resulting in increased erosion may be active regional uplifting. As the basin is progressively being uplifted, downcutting of streams ensues, causing oversteepening of slopes with eventual slope failure.

Geology

32. The geology of the Eel River Basin is highly variable and complex. Most of the rocks are deepwater marine sedimentary and mafic marine volcanic materials ranging in age from late Jurassic to Cretaceous. The sediments were deposited in a submarine trough accompanied

Figure 17. Aerial view of central
Eel River Basin

by sporadic volcanic activity. The trough experienced uplift, folding, and faulting near the end of Cretaceous continuing through Cenozoic time. Active mountain building has taken place in Miocene, Pliocene, and Pleistocene time, as evidenced by terraces along the coast.

33. Most of the Eel River Basin is underlain by the Franciscan formation (Figure 23). The formation, as described by Page (1966), is a complex assemblage of sandstone, largely serpentinized basic and ultrabasic rocks, and volcanics altered to greenstone. Graywacke is the prevalent sedimentary material, associated with small amounts of shale. The general strike is north 30 deg west with an eastward dip.

Figure 18. Eel River near Mail Ridge

Figure 19. Van Duzen River near Carlotta

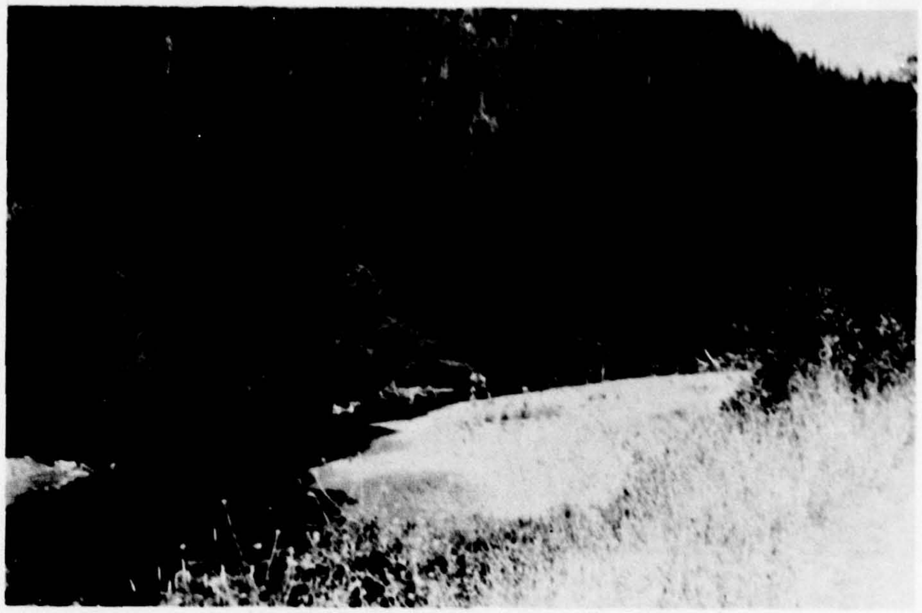


Figure 20. Steep, forested slopes on South Fork near Weott

Figure 21. Steep, grassed slopes on Mail Ridge, central Eel River Basin

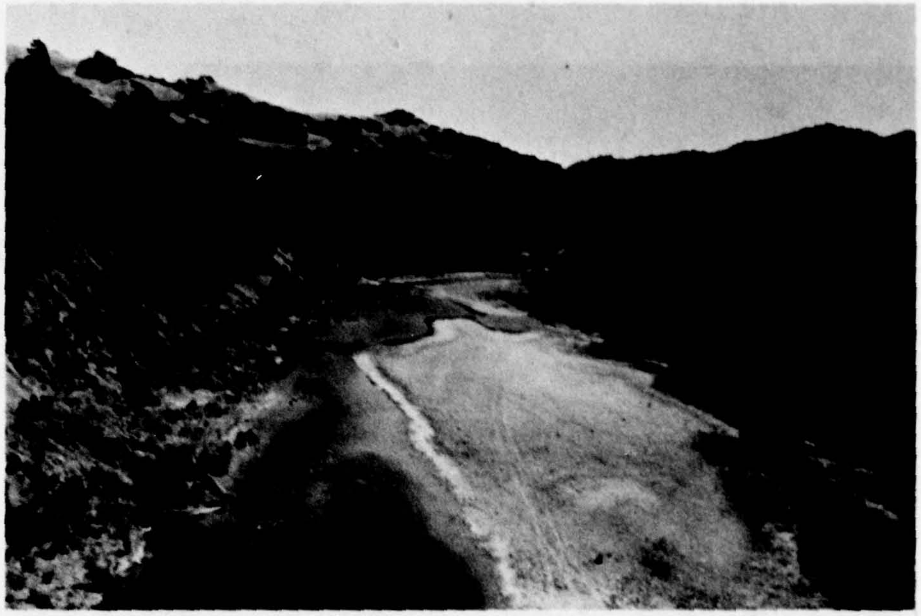


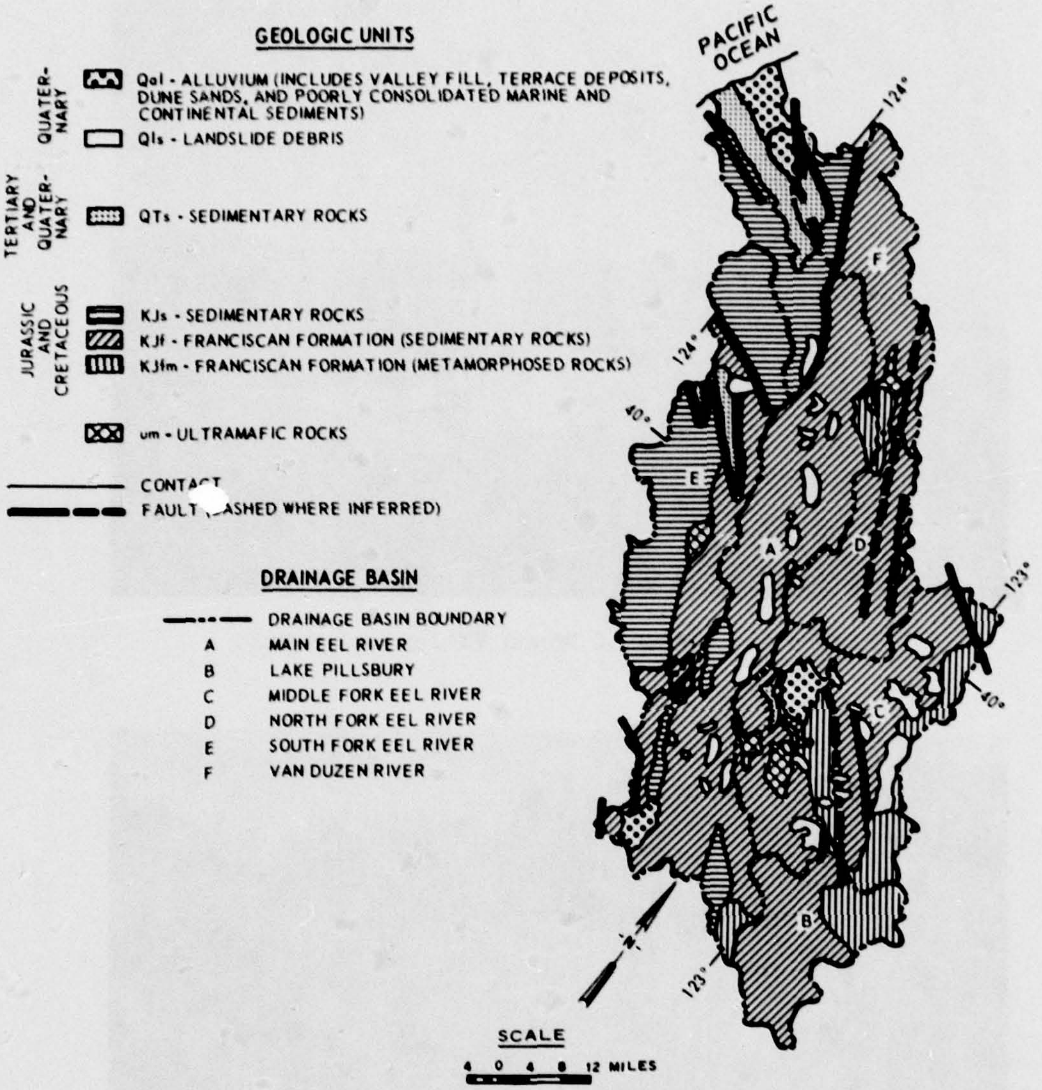
Figure 22. Eel River at Alderpoint

The formation has been separated into three broad belts.

34. The Coastal belt, youngest in age (Cretaceous), is largely unmetamorphosed sedimentary materials of sandstone, shale, and conglomerate. The Central belt is more heterogeneous and includes sandstone, shale, conglomerate, and greenstone with occurrences of limestone, glaucophane schist, chert, and serpentine. The Eastern belt is similar to the Coastal belt but has experienced metamorphism. Local rock types include foliated sandstone, slate, phyllite, and quartz-mica schist.

35. Sediments of late Cretaceous and Tertiary time are found along the western perimeter and in the Eel River valley along the main channel. In several localities, downfaulting of blocks with concomitant filling has formed filled valleys, e.g. Round Valley (Figure 24), Little Lake Valley, and Laytonville Valley.

36. The nature of the geologic materials present in the Eel River Basin also encourages high erosion rates. For the most part, the Franciscan formation underlying about 80 percent of the basin is highly unstable due to structural and compositional weaknesses. Large and small faults and shear zones are relatively numerous throughout the



(Geology From California Dept. Of Water Resources, 1966)

Figure 23. General geology of the Eel River Basin

basin. The deeply weathered sandstones contain local amounts of shale and serpentinite. These characteristics and the rugged topography result in high natural erosion potential. The very unstable nature of geologic materials throughout the basin is evident in the large number of debris slides, debris torrents, and earth flows (Figures 25 and 26). These widespread activities may substantially increase the amount of

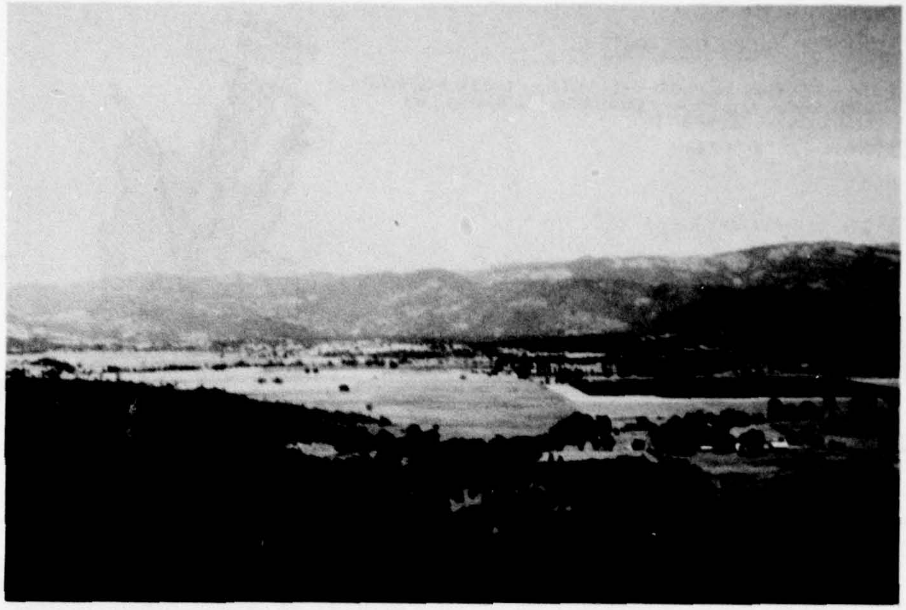


Figure 24. View of Round Valley and Covelo

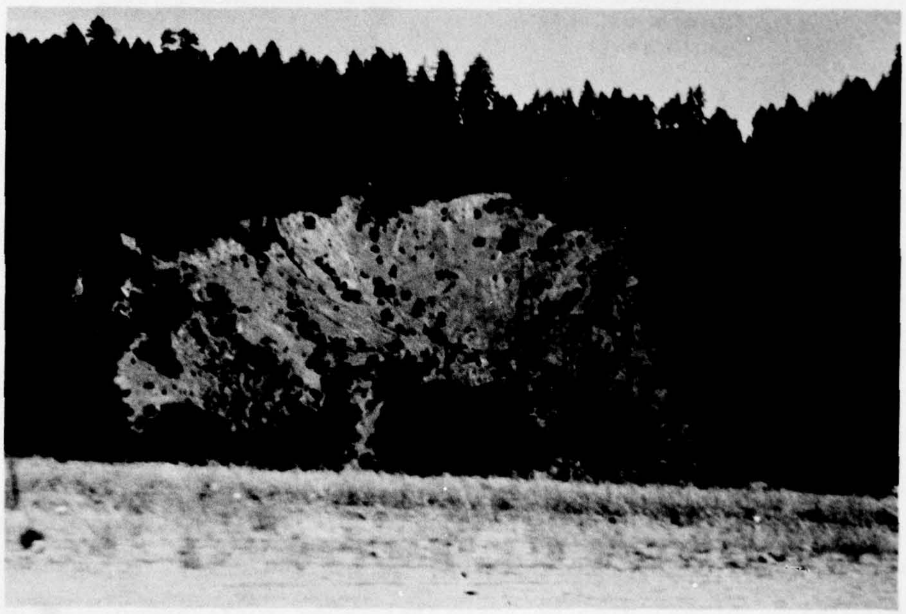


Figure 25. Debris slide adjacent to South Fork,
2 miles south of Garberville

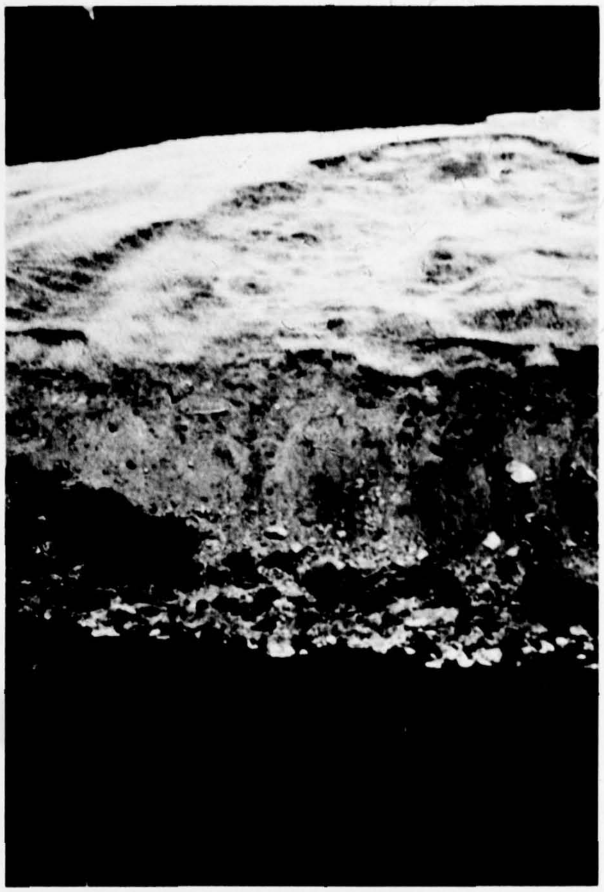


Figure 26. Slump and earthflow adjacent
to South Fork, 3 miles south of Phillipsville

sediment moved by the streams at the demonstration sites.

Soils

37. As reflected in the complex geologic environment, soils of the Eel River Basin are also highly variable. However, a predominance of sedimentary materials has resulted in several dominant soil series, including the Hugo, Josephine, Laughlin, and Maymen series. The Hugo and Josephine soils are moderately deep to deep and medium textured, developed under forests on moderate to steep slopes. Infiltration characteristics are good and the soils are stable under native vegetation. The Laughlin series consists of prairie soils of oak-grass open lands. Found on ridge tops and moderately sloping areas, these soils

are of medium texture and average 24 in. in depth. Under native cover Laughlin soils are fairly stable but may become highly unstable when vegetative cover is removed.

38. Soils of the Maymen series occupy steep slopes covered by brush. These medium-textured soils are very shallow but the bedrock is usually highly shattered, enhancing permeability. Stability is surprisingly high due to the presence of gravel-size rock throughout the profile, which acts as an "erosion pavement."

39. Soil erosion potential may be associated with geologic erosion susceptibility. Soil erosion hazard is based on land slope, soil texture and structure, type and density of vegetative cover, and the amount of runoff. Classes of soil erosion hazard include low, moderate, high, and very hazardous when vegetative cover is removed. These categories make up 5.0, 14.0, 52.6, and 28.4 percent of the basin area, respectively (U. S. Department of Agriculture (USDA) 1970) (Figure 27). Most of the soils of the basin have at least a high soil erosion hazard or potential.

Hydrography

40. The Eel River drainage system is composed of approximately 10,000 miles of channel, including the Eel and its tributaries. The major tributaries are the Van Duzen River, Black Butte River, and north, middle, and south forks of the Eel River (Figures 28-31). Numerous small lakes, ponds, and farm reservoirs occur throughout the basin but are relatively insignificant as sources of storage. Lake Pillsbury, impounded by Scott Dam in the headwaters of the Eel, has a storage capacity of 86,780 acre-ft (Porterfield and Dunnam 1964).

41. Annual and monthly runoff is quite variable, being directly related to amount of rainfall (Figure 32). Due to the rugged topography and natural lack of storage, runoff regimes closely parallel precipitation events once soils become saturated during the first storms of early winter. Little runoff is realized from rare summer precipitation. Baseflow is poorly maintained during summer months when streams which raged in winter months are reduced to a trickle. Flow is partially regulated by Scott Dam at Lake Pillsbury and the Potter Valley Tunnel

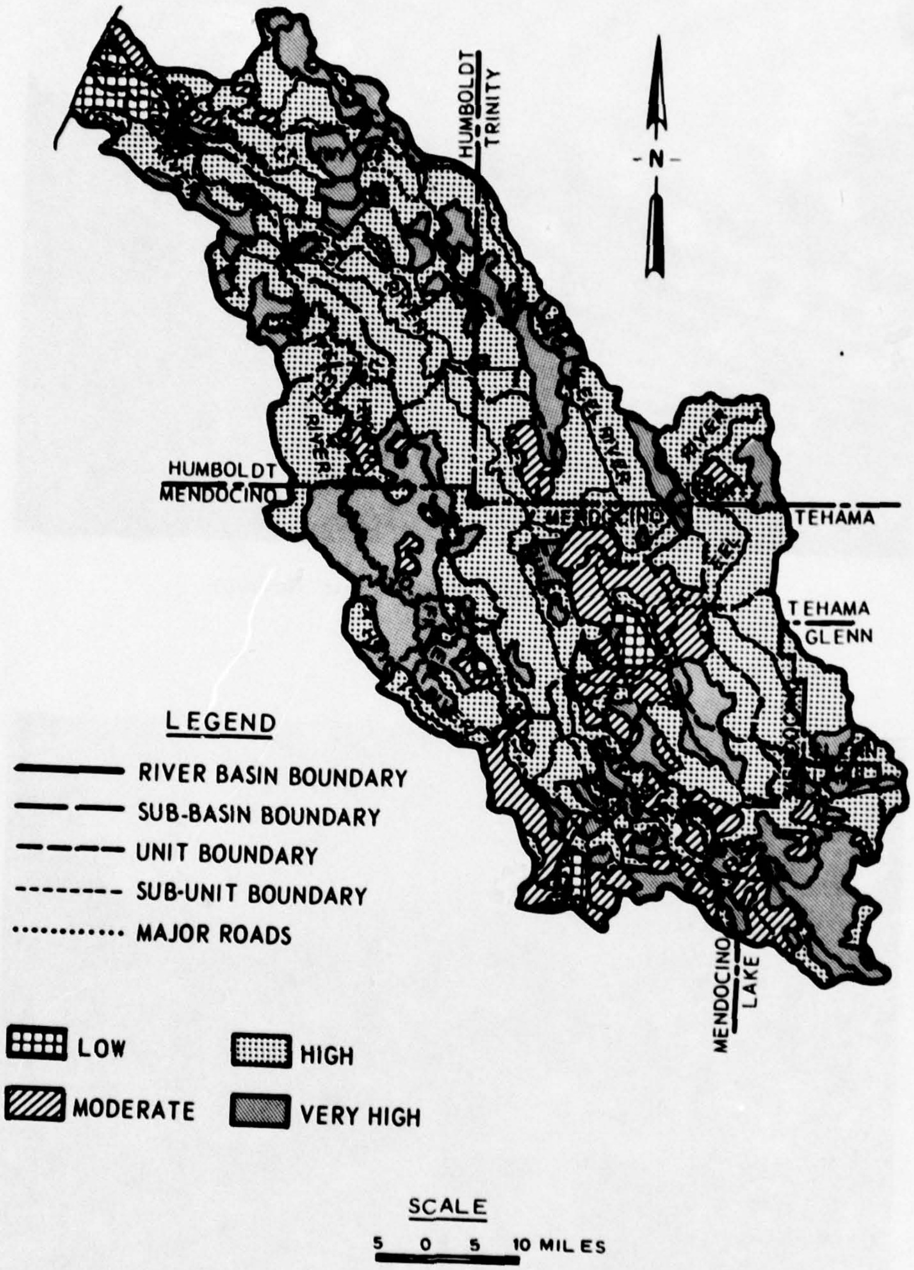


Figure 27. Distribution of soil erosion hazards in Eel River Basin

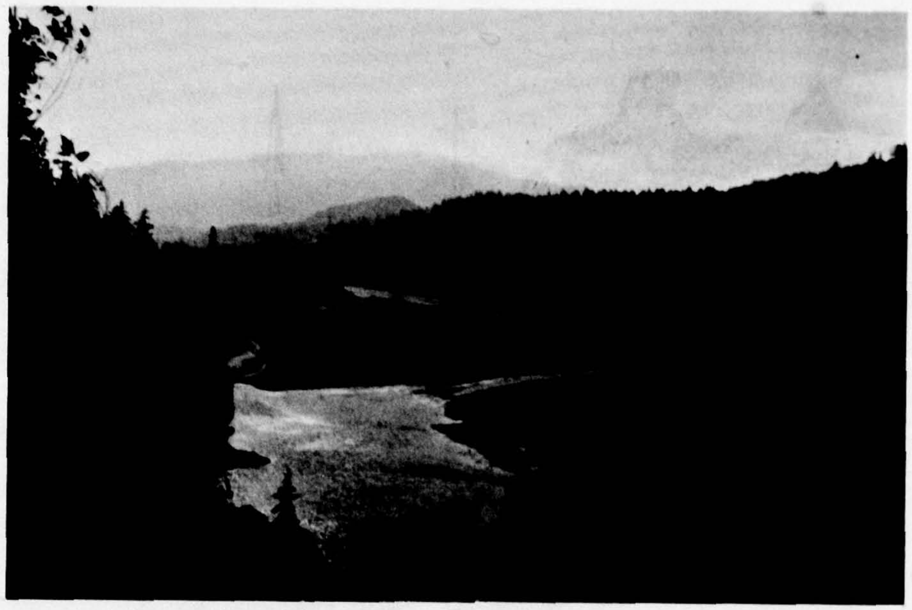


Figure 28. Eel River near McCann

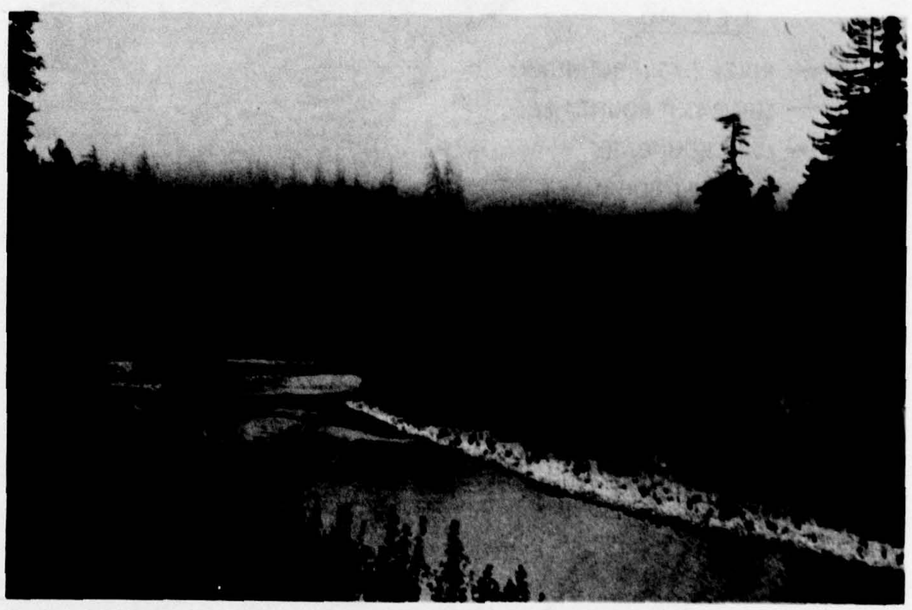


Figure 29. Van Duzen River near Strongs Station

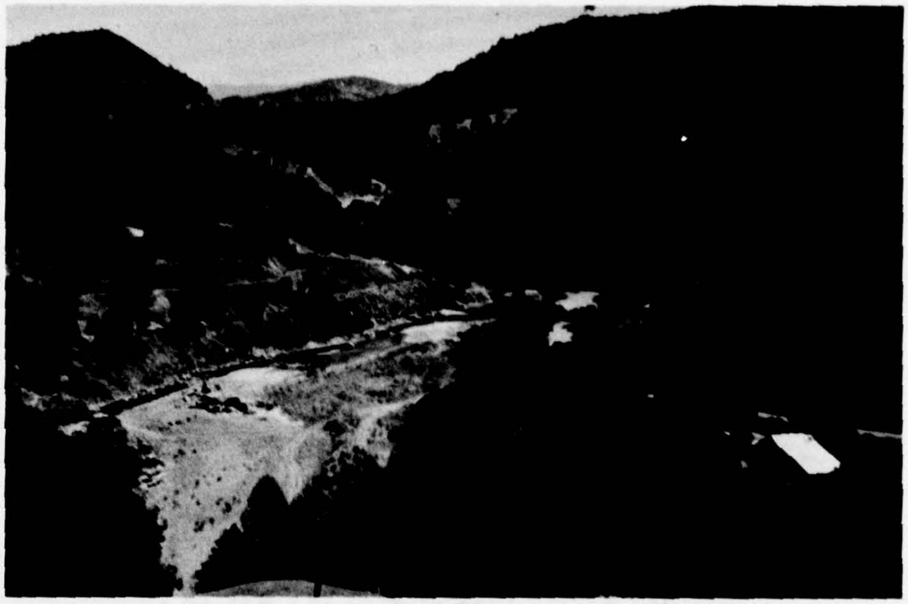


Figure 30. Middle Fork, Eel River, at Dos Rios

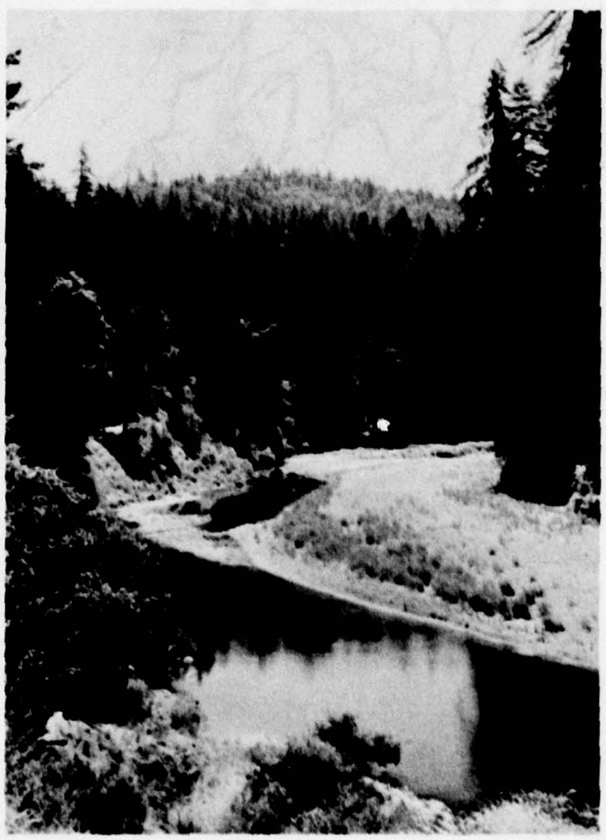


Figure 31. South Fork, Eel River, near Myers Flat

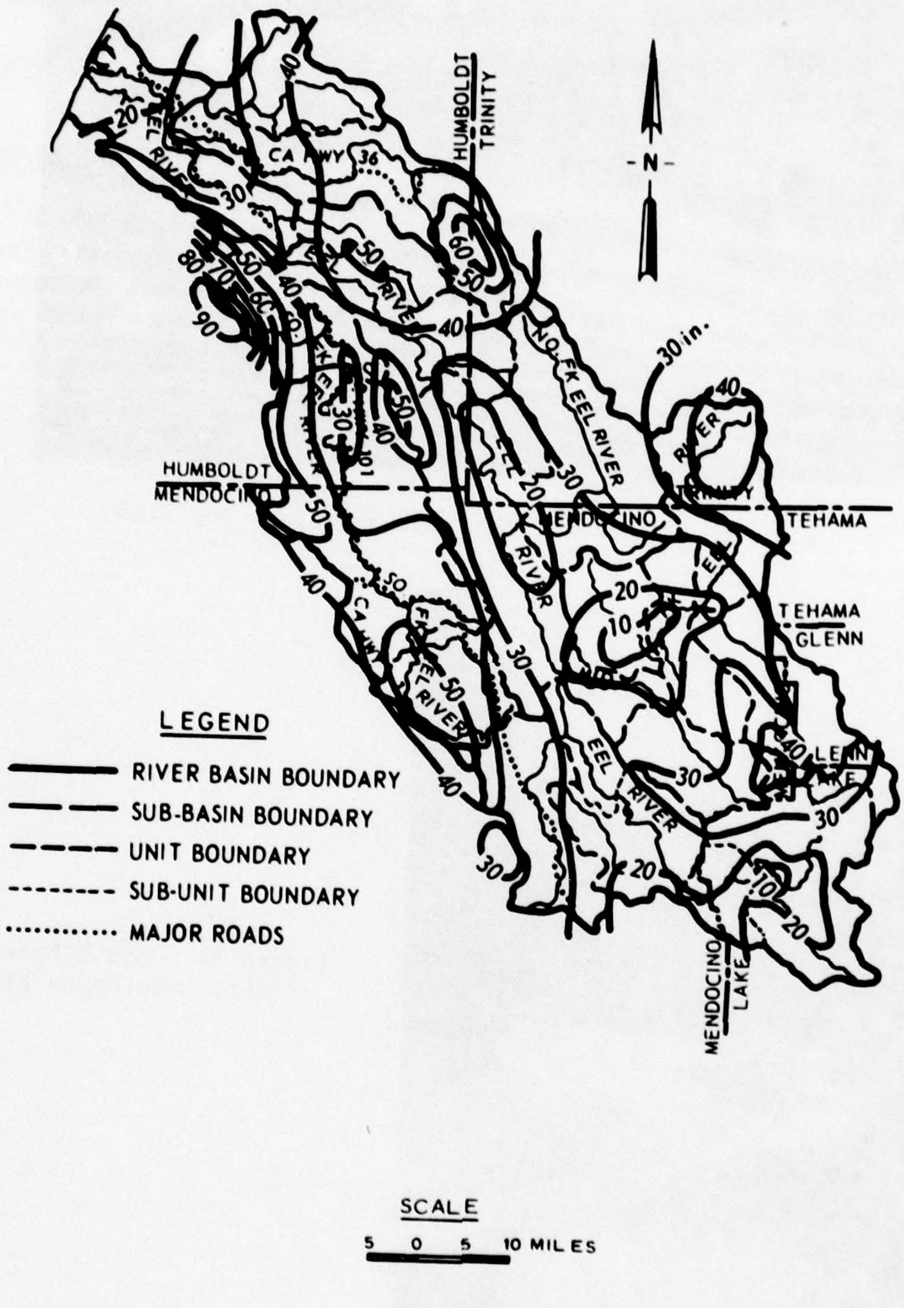


Figure 32. Average annual runoff in Eel River Basin

at Van Arsdale Dam, which diverts roughly one third of average flow of the Eel at that point to the Russian River basin. Streamflow recorded on the Eel at Scotia (86 percent of drainage basin) ranges from 10 cfs to 752,000 cfs. Annual runoff from an average 59 in. of precipitation is 35 in. (6,808,000 acre-ft) (Rantz 1968).

Climate

42. Of paramount hydrologic importance to the mechanics of drainage basins and their streams is the stochastic influence of climate, which determines the amount of water entering the basin system. Climate controls water input directly through precipitation and evaporation and indirectly by influencing vegetation type and distribution.

43. The climate of the Eel River Basin is composed of regional variations of the Mediterranean type (James 1959). Several factors strongly influence the development of this major climatic type and its regional variations. The proximity of the Pacific Ocean tends to moderate temperature regimes, causing a decrease in summer temperatures and an increase in winter temperatures. This effect is diminished, however, with distance inland. The northwest-southeast trending coastal ranges serve as highly effective orographic barriers to precipitation (Figure 33). Average annual precipitation is highly dependent upon altitude and location in reference to orographic barriers (Figure 34).

44. An additional climatic control is the semipermanent high pressure system of the north Pacific Ocean. Migration of this area of high pressure northward during the summer draws storm tracks northward, resulting in a distinct dry season. Conversely, southward migration of the high pressure during winter months brings storm paths directly through the Eel River Basin, causing a preponderance of precipitation. The north Pacific high also serves to drive the California current, which causes upwelling of cold water directly off the coast. Relatively warm air masses moving inland over this cold water zone during summer months cause dense fog along coastal areas and usually extend to elevations of 1500 to 2000 ft.

45. The effect of these climatic controls upon precipitation and temperature regimes of locations within the Eel River Basin is evident

Figure 33. Orographic control of cloud movement by coastal mountains, 2 miles north of McCann

in Table 2. Scotia, situated relatively close to the coast at a comparatively low elevation, has a strongly moderated temperature and precipitation regime. Further inland to the south and much higher in elevation, Cummings receives much more precipitation than Scotia. The data for Alderpoint reflect a climate still further removed from the moderating effects of the Pacific. Covelo is most distant from the Pacific and most removed from precipitation-producing events.

46. Climatic characteristics of the Eel River Basin are highly conducive to the active modification of the landscape by running water. Precipitation amounts, although extremely variable in both temporal and spatial distribution, are relatively high for most of the basin. Additionally, most of the precipitation and runoff occurs during winter months when evaporation is insignificant and the erosive power of streams is at a maximum.

47. The importance of climatic characteristics on streambank erosion is exemplified in the occurrence of floods. The impact of floods on channel morphology depends upon the magnitude or frequency of

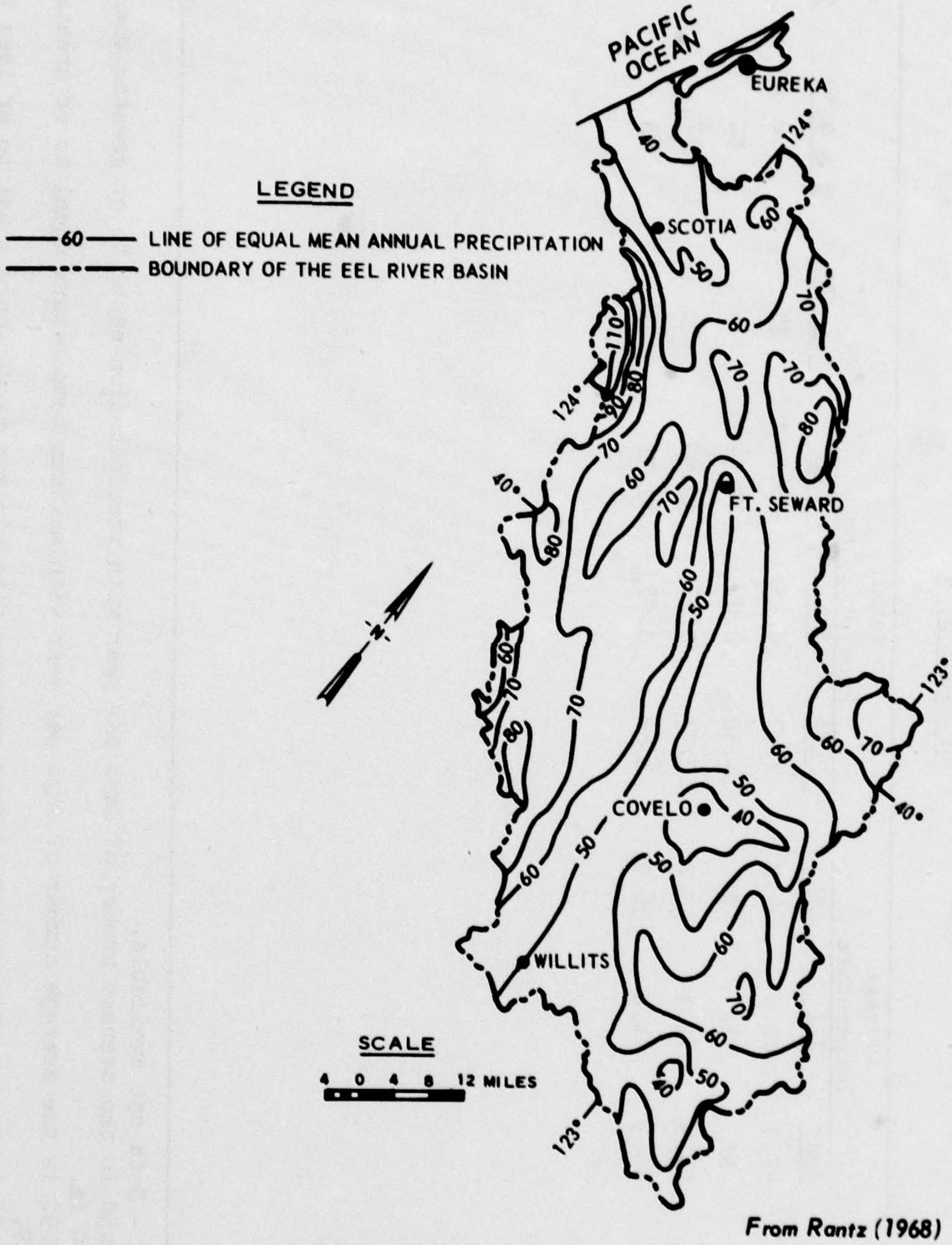


Figure 34. Mean annual precipitation over the Eel River Basin, 1900-1963

Table 2

Climatic Data

	Average Temperature			Total Precipitation					
	Jan	Jul	Ann	Jan	Jul	Ann	$P \geq 50$*	$T \geq 90$**	$T < 32$†
Scotia	47.7	61.0	54.9	9.42	0.05	48.50	35	0	3
Cummings	NA	NA	NA	14.52	0.05	70.94	45	NA	NA
Alderpoint	44.3	72.3	57.7	10.77	0.02	53.40	36	57	36
Covelo	40.3	74.0	56.0	8.68	0.08	41.14	31	85	94

Note: NA = Data not available.

* $P \geq 50$ is the average number of days per year with precipitation equal to or greater than 0.50 in.

** $T \leq 90$ is the average number of days per year with maximum temperature equal to or greater than 90°F.

† $T \leq 32$ is the average number of days per year with minimum temperature equal to or less than 32°F.

occurrence, the size of the drainage basin, and the morphogenetic region. While Wolman and Miller (1960) have demonstrated that climatic events of moderate frequency are more significant than catastrophic floods in modifying certain landscapes, it has also been suggested that large, rare floods may profoundly alter basin and channel morphology in certain environments (Baker 1977).

48. The effect of floods upon stream channels and sediment sources in the Eel River Basin has been well documented (Waananen, Harris, and Williams 1971). In December of 1964, the Eel River experienced a flood with a return frequency of greater than 100 yr. Precipitation in some locations exceeded 20 in. in a 48-hr period, sending river stages as much as 15 ft above previous record stages. Erosion from streambanks, landslides, and sheet flow caused tremendous sediment yields. For a 3-day period beginning 22 December 1964, suspended sediment discharge on the Eel at Scotia was computed at 116 million tons. This total exceeded the yield of 94 million tons for the previous 8 yr. New water and sediment discharge records were established at all gaging stations within the basin.

49. This catastrophic flood resulted in substantial alteration of channel morphology in the Eel basin. Hickey (1969) found that as a result of the flood, sediment deposition caused streambed elevations to rise 6 to 8 ft in the vicinity of the confluence of the Middle Fork and Black Butte Rivers (Figures 35 and 36). He also noted that deposition continued during the next water year. Kelsey (1975) noted similar changes in streambed elevations of the Van Duzen River (Figures 37 and 38). An additional impact of the flood was to trigger extensive mass-wasting events throughout the basin, which contributed greatly to sediment discharge.

50. As stated in the discussion of basin hydrology, runoff is closely associated with precipitation. Streamflow is highly responsive to winter storms, causing rapid fluctuation of stream stages. Streambanks are therefore subject to frequent saturation and drawdown rates, increasing bank instability. The effect of freeze and thaw of bank materials as a preparation for erosion is of less significance at the

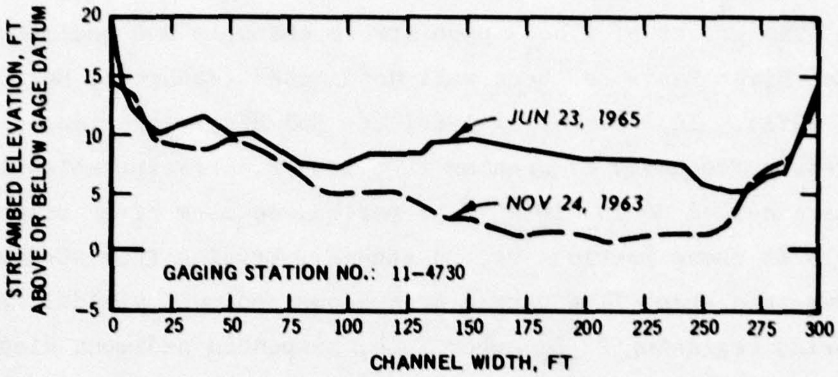


Figure 35. Cross sections of Middle Fork below Black Butte River near Covelo

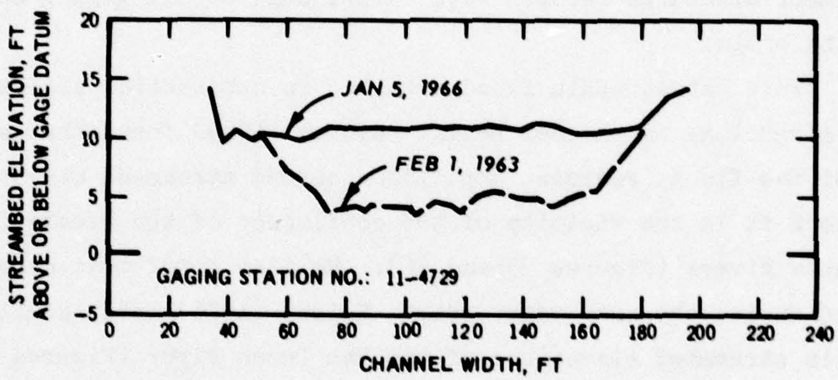


Figure 36. Cross sections of Black Butte River near Covelo

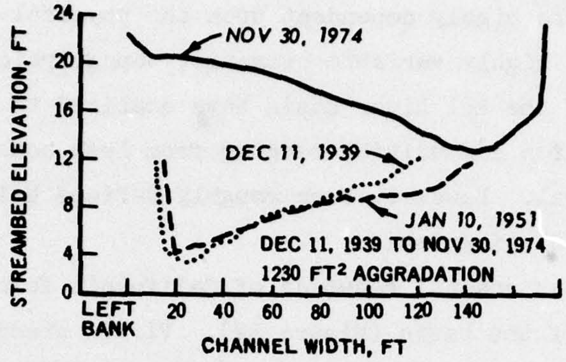


Figure 37. Cross sections of Van Duzen River near Bridgeville

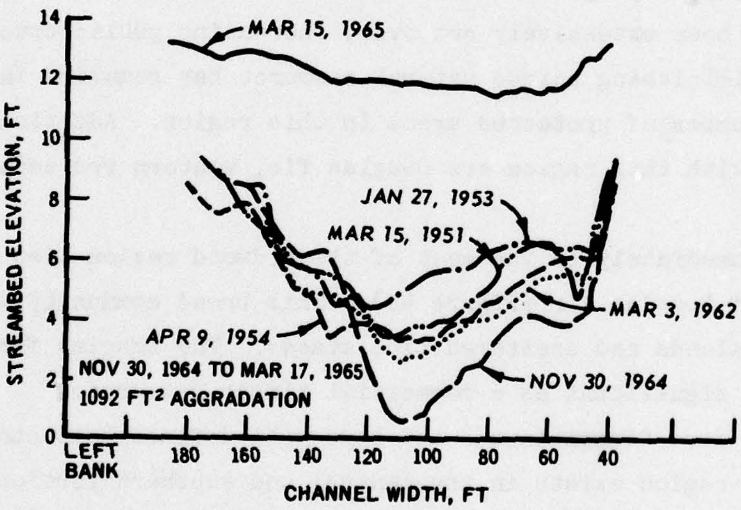


Figure 38. Cross sections of Van Duzen River at Pepperwood Falls

demonstration sites but it may be of substantial importance further inland at sites receiving greater annual and diurnal temperature variation.

Vegetation

51. As is the case with basin hydrology, natural vegetation type and distribution are highly dependent upon the physical characteristics of the basin. The highly variable climatic, topographic, and edaphic characteristics of the Eel River Basin have combined to produce a wide variety of vegetation communities ranging from lush coastal forests to dry upland chaparral. However, four roughly defined belts of vegetation types may be distinguished.

52. The famous coastal redwoods of California form a belt along the western side of the basin (Figure 39). Virgin stands may include trees with heights of 300 ft, ranging from 500 to 800 yr old. Unique physical properties of the trees place them in great demand by commercial timber operations and recreationists. Although many of the virgin stands have been extensively cut over, increasing public concern over a rapidly diminishing unique natural resource has resulted in the creation of a number of protected areas in this region. Additional species associated with this region are Douglas fir, western red cedar, and madrone.

53. Immediately to the east of the redwood region lies an extensive belt of Douglas fir (Figure 40). This broad community also includes grasslands and scattered pine stands. The Douglas fir belt is also highly significant as a commercial timber resource.

54. A more discontinuous and less well-defined belt east of the Douglas fir region exists in the central and southern portions of the basin (Figure 41). Dominant vegetation consists of a variety of hardwoods (oaks, maple, and madrone), scattered mixed conifers (ponderosa, jeffrey, and sugar pines), and chaparral. The hardwood areas are frequently interspersed by expanses of natural grasses. Chaparral, consisting of a variety of evergreen shrubs, scrub oaks, and chamisa, as well as natural grasses, occupies the drier slopes to the south.

55. In the higher elevations of the eastern extremities lies

Figure 39. Redwood forest: Avenue of the Giants (U. S. 101) near Pepperwood

another belt of mixed conifers. Dominant vegetation includes Douglas fir and fir, various pines, and scattered woodlands (Figure 42). The dominance of conifers, especially Douglas fir, makes the region an important timber resource.

Man-Induced Factors

56. Contributions of man's activities in drainage basins to alterations of water and sediment discharge have received much attention in the literature. Some land use practices and activities are especially effective as modifiers of streamflow and sediment yield regimes.

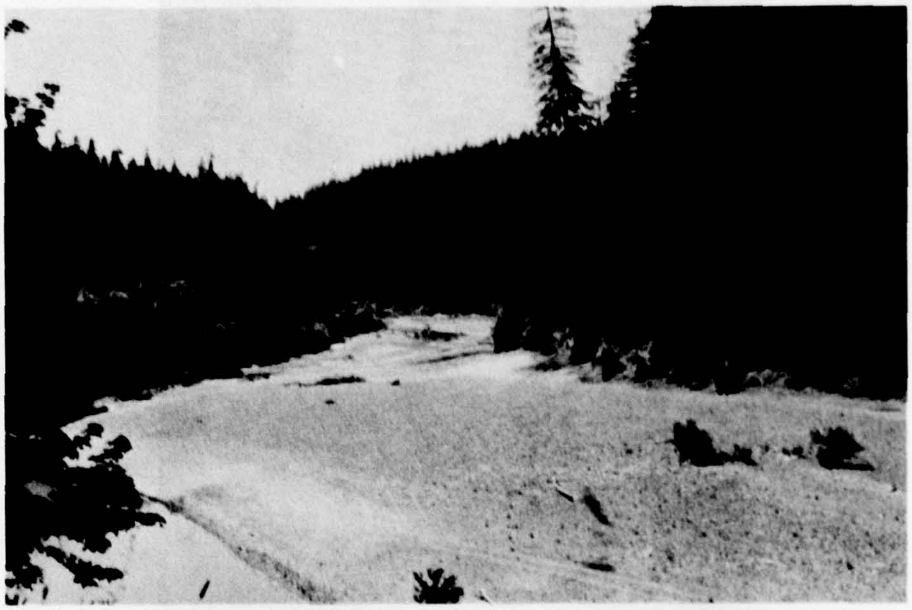


Figure 40. Douglas fir along South Fork near Weott

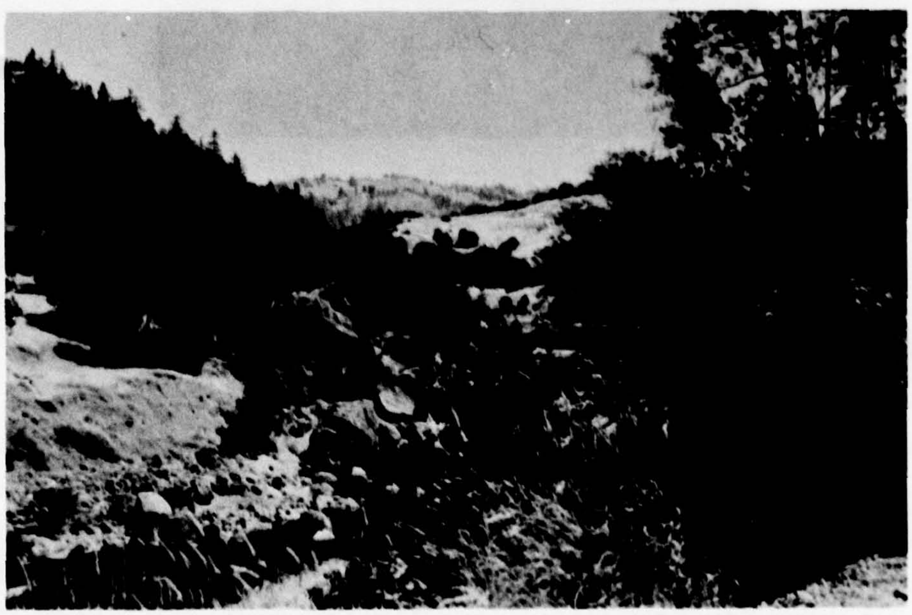


Figure 41. Hardwoods and grassland along South Fork near Phillipsville

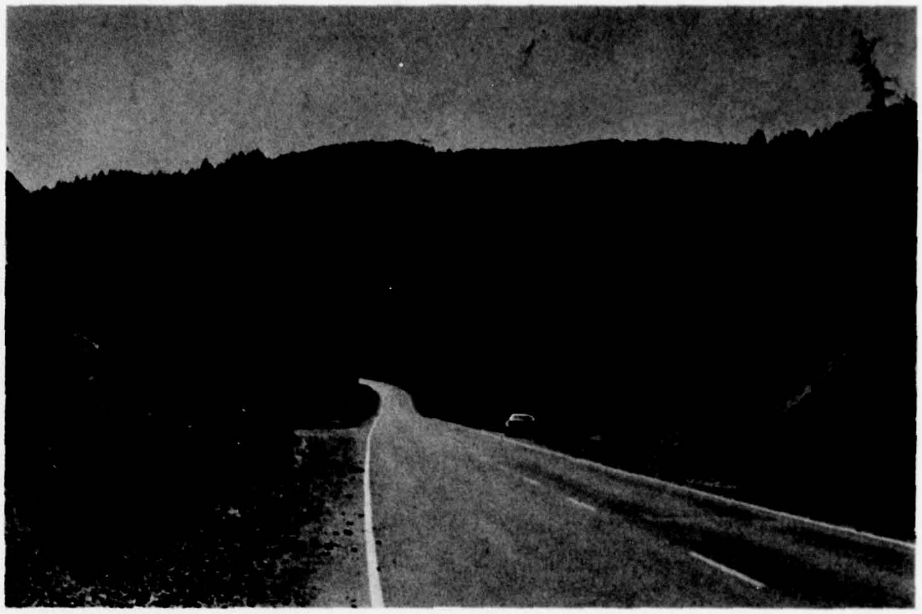


Figure 42. Douglas fir and other conifers, road cut near Hetten Valley, western Trinity County

Previous investigations of the impact of man's activities in the Eel River Basin have resulted in a variety of conclusions (Anderson 1970, USDA 1970).

57. Land utilization of the Eel River Basin is strongly related to vegetation type and distribution. The commercial timber industry is by far the most extensive and economically important land use activity in the basin. Large expanses of valuable timber species have attracted the logging industry for over 100 yr. As a result, much of the forest has been cut over and exists in some stage of second growth (Figures 43 and 44). Some cut-over areas have been maintained in grass for grazing purposes.

58. Agriculture is of limited importance due to the small amount of land suitable for cultivation. Agricultural activities are usually divided into dry-farmed and irrigated categories. According to the California Department of Water Resources, dry-farmed areas comprise about 32,000 acres in the Eel delta and in scattered locations throughout the basin (Figure 45). Irrigated lands cover approximately 14,500

Figure 43. Evidence of logging on steep slopes along the Van Duzen River, near Dinsmores

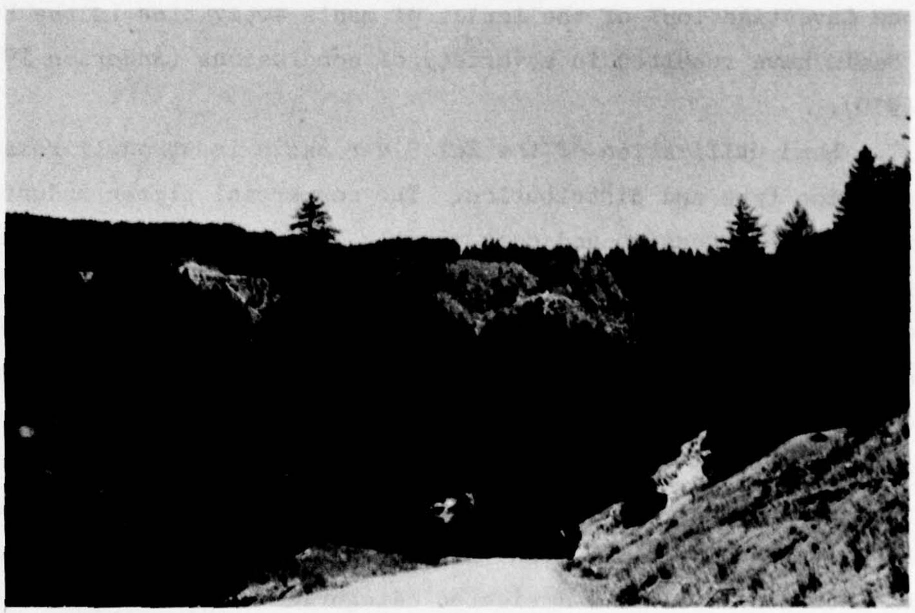


Figure 44. Evidence of logging on steep slopes near Hetten Valley, western Trinity County

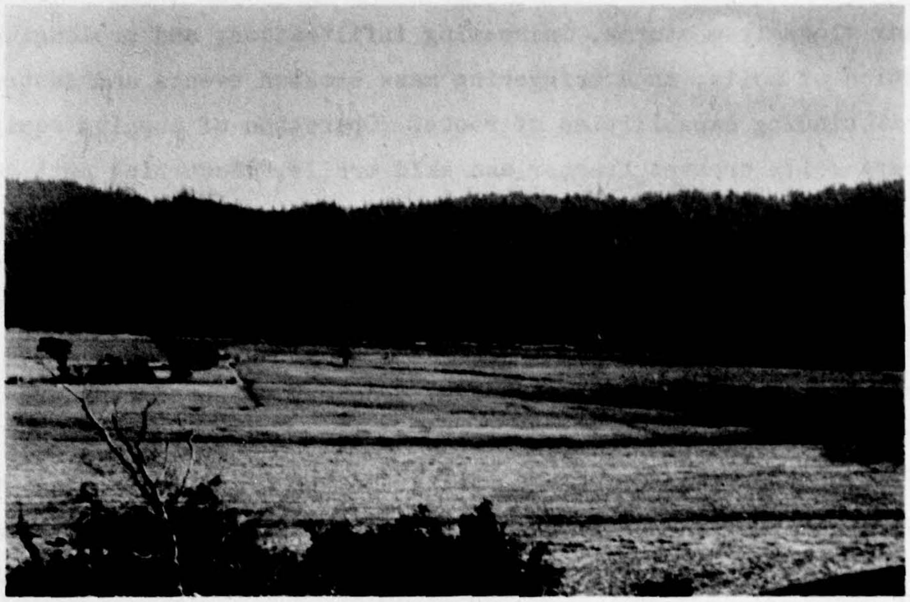


Figure 45. Dry-farmed area in lower Van Duzen River valley near Carlotta

acres in the Eel delta and the previously mentioned fault-block valleys. Forage corps for dairy cattle make up the majority of agricultural activity (California Department of Water Resources 1965).

59. Urban areas are comparatively small and widely spaced along the major streams. Population of the basin is estimated at 50,000. Recreation facilities total approximately 28,000 acres.

60. Logging and associated activities, the predominant form of land utilization in the Eel River Basin, may have a tremendous impact upon the hydrologic regime of a drainage basin. Of primary importance is the type of logging practiced. Most logging in the Eel River is done by tractor or chain logging. While both are extremely deleterious to the stability of natural slopes, tractor logging probably results in the greatest increase of erosion susceptibility. Both procedures involve complete removal of vegetation from large areas (see Figures 43 and 44).

61. Erosion damage resulting from logging practices is due to a number of conditions caused by the procedures used to cut and transport timber. The most evident impact is created by the removal of vegetative

cover. Loss of vegetative cover alters the hydrologic budget by increasing peak flows from storms, increasing infiltration, and prolonging saturation of soils, thus triggering mass erosion events and destroying the soil binding capabilities of roots. Operation of logging equipment on forest soils creates tractor and skid trails, disturbing soil characteristics and creating runoff channels. Logging roads are usually poorly constructed, interrupting surface and subsurface drainage and causing increased sediment loads. Slash and debris often enter downslope stream channels and may temporarily retain streamflow. When streamflow breaches the temporary dam, accelerated streambank erosion may occur immediately downstream.

62. Another land use activity that may be significantly altering natural streamflow and sediment yield regimes is the construction of roads. The impact of unimproved roads has already been presented in the discussion of logging practices. More permanent roads may also interrupt hydrologic characteristics of slopes and channels. Steep, bare road cuts encourage increased sediment yields from sheet, rill, and gully erosion (Figure 46). Natural surface and subsurface drainage may be impeded or rerouted. Inadequate and misaligned culverts often increase streambank erosion and hence sediment production downstream. Furthermore, misalignment of bridges causes turbulence and flow detection, also encouraging streambank erosion.

63. Grazing of natural grasslands is the second most extensive land use practice occurring in the Eel River Basin (Figure 47). Some areas have experienced grazing for over 100 yr. As a result, natural perennial grasses have been removed and replaced by more exotic annuals. The annual cover represents a decrease in protection from sheet, rill, and gully erosion. It has been determined that approximately one third of the grassland in the basin is deficient in protective vegetal cover (USDA 1970). This problem is especially apparent on private lands that are grazed year-round.

64. Some areas that have undergone timber harvesting have been converted, sometimes on an extensive scale, to grassland for grazing purposes. Sediment yields from timber areas converted to grassland are

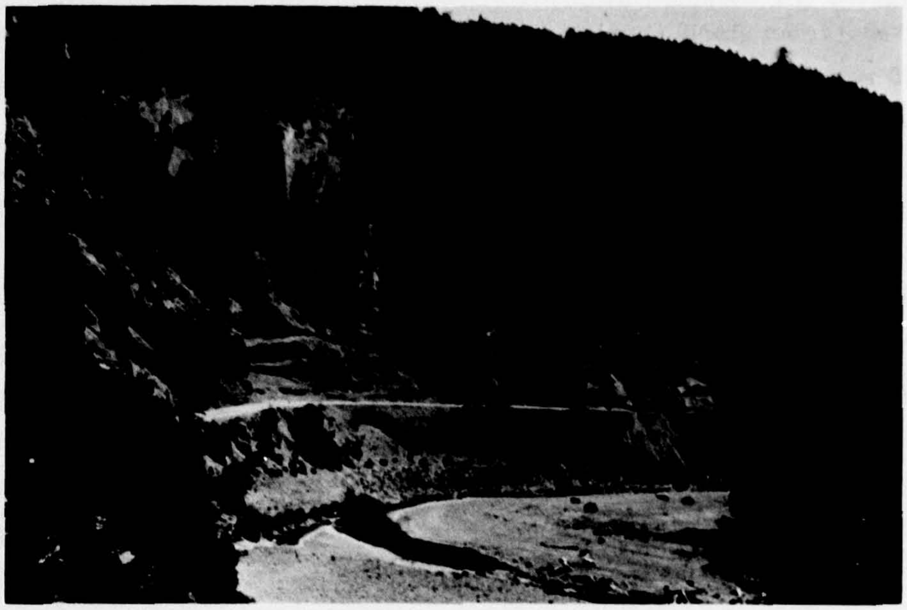


Figure 46. U. S. Highway 101 adjacent to South Fork near Piercy

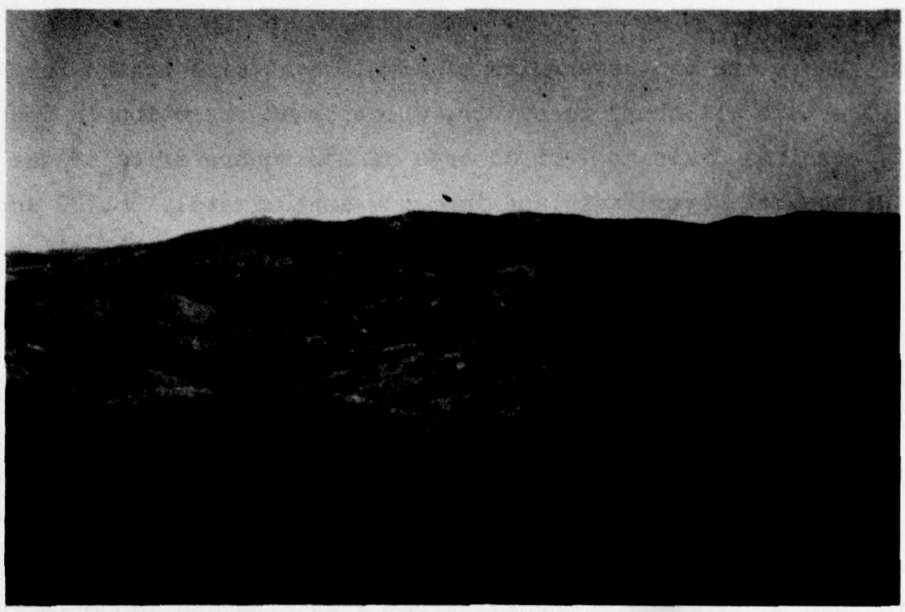


Figure 47. Natural grassland, Mail Ridge, central Eel River Basin

greater than yields from natural grasslands due to several factors. Converted timber land usually has more bare ground. Soils developed under forests are usually more acidic than natural grassland or prairie soils and are more conducive to the growth of trees than grasses. Consequently, quality and density of cover is usually considerably lower than natural grassland areas with a resultant higher sediment and runoff yield.

65. One of man's impacts upon the hydrologic environment of drainage basins may be the alteration of channel morphology and flow regime. These modifications by man are usually embodied in channel straightening and construction of reservoirs. The impact of reservoirs upon streamflow and sediment discharge has been widely stated in terms of modification of maximum and minimum streamflow, flattening of flood hydrographs, and increased loss due to evaporation. Reservoirs also effect removal of sediment load from the drainage system above the reservoir with varying efficiency. As a result, relatively clear water is released downstream from the reservoir, causing increased erosion of channel bed material with associated oversteepening of banks for some distance downstream.

66. There are two reservoirs of significant size in the Eel River Basin. The Lake Pillsbury reservoir, which began operation in December of 1921, receives drainage from an area of 288 square miles in the headwaters of the Eel River Basin and impounds approximately 86,780 acre-ft of water. Van Arsdale Reservoir is located approximately 11 miles downstream from Lake Pillsbury and has a drainage area of 349 square miles. The Van Arsdale reservoir, operating since 1909, has a relatively small storage component, with its main function associated with the diversion tunnel (see paragraph 41). Although both reservoirs serve to accomplish the aforementioned impacts to the drainage system, the impact of the reservoirs on current streambank erosion at the demonstration sites is probably minimal. Length of time since beginning of operation (68 and 56 years) and distance from the Eel River site (149 and 160 miles) are modifying factors that diminish the impact of the reservoirs on streambank erosion at the Eel River site.

PART V: ANALYSIS OF FACTORS

Combination of Factors

67. The individual factors affecting streambank erosion at the demonstration sites, both at the site and upstream, collectively form a complex hydrologic system. The magnitude and extent of each factor is affected in some degree by several or all of the other factors. The general relations between the various factors or variables that are affecting bank erosion in the Eel River delta are shown in Table 3. Independent and influencing variables are listed in the vertical column on the left. Variables that are dependent, that is, influenced by the independent and influencing variables, are listed across the top of the table. Independent variables are marked by asterisk; site factors are indicated by a rectangular outline; and links between site and nonsite factors are circled. The "X" indicates a controlling relationship. For example, consider the influencing factor "topography" in the vertical list. The table explains that topography influences soils, landslides, vegetation, runoff, and basin flows. On the other hand, topography is influenced by climate, lithology, landslides, roads, and structure/tectonics. Note that only two factors directly link site and nonsite factors: basin flows and sediment yields. The following paragraphs discuss the nature of these linking factors.

Impact of Floods

68. The magnitude of the unprecedented recorded flood of 1964 in both water and sediment discharge was a product of not only the natural characteristics of climate, geology, soils, topography, hydrography, and natural vegetation but also of possible modifications of these characteristics by man's activities. Anderson (1972) investigated the ability of drainage basins in northern California to return to normal after the 1964 flood in terms of certain characteristics of the basins. Using principal component analysis, he determined that 85 percent of the

Table 3

Influences of Site and Nonsite Factors

Eel River, California

Independent & Influencing Variables \ Dependent Variables	Soils	Landslides	Vegetation	Topography	Sediment Yield	Runoff	Channel Widening	Channel Deepening	Sinuosity Changes	Flow	Channel Width	Channel Depth	Channel Slope	Bank Materials	Sediment discharge	Flows (Basin)	Bank Erosion
Flow							X	X	X		X	X	X	X	X		
Topography	X	X	X			X										X	
Sediment Discharge							X	X	X		X	X	X	X			
Soils		X	X		X	X											
Climate*	X		X	X		X											
Bank Materials							X	X	X	X							
Lithology*	X	X		X													
Flows (Basin)		X			X					X							
Landslides	X			X	X												
Vegetation	X				X	X											
Runoff		X			X											X	
Forestry*	X		X														
Roads*			X	X													
Structure/Tectonics*		X		X													
Grazing*			X														
Channel Width										X							
Channel Depth										X							
Channel Slope										X							
Channel Widening																	X
Channel Deepening																	X
Sinuosity Changes																	X
Sediment Yields															X		

* Independent variable.

Flow Site factor.

X Link between variables.

X Links between site and nonsite factors.

variance in the amount of time required to return postflood sediment discharge to magnitudes similar to preflood discharges could be explained by five variables: initial acceleration of sedimentation by the flood, topographic path lengths (of overland flow), indices of land use prior to the flood, area of steep grassland, and geologic rock type. Anderson's conclusions suggest that abnormally high sediment discharges associated with large floods are largely a function of four physical factors and a cultural factor (acres per square mile of "poor logging") of the drainage basin.

Effect of Landslides

69. Other such natural phenomena that result from the combination of alteration of naturally fragile environments are landslides of various types. Landslides pose a significant natural hazard in the Eel River Basin and comprise a tremendous sediment source (Cleveland 1977). A typical sequence of events associated with the occurrence of landslides in the Eel River Basin might be the following:

- a. Removal of forest vegetation and construction of logging trails, spurs, and landings.
- b. Increased infiltration and prolonged saturation of soils.
- c. Soil creep with down slope accumulation.
- d. Slope failure in the form of slumping with flow of toe material into channel.
- e. Deflection of streamflow against opposite banks, causing erosion.
- f. Erosion of toe of earthflow and oversteepening of opposite banks.
- g. Failure of opposite bank, causing a repetition of the cycle.

Several factors strongly influence landslides. In a survey of mass-wasting events in the Van Duzen River Basin, debris slides, earthflows, and undifferentiated landslides were studied in terms of several characteristics. These factors were geologic materials, slope, vegetative cover, proximity to streams, roads, and shear zones and faults, and

size. The resulting conclusions were determined as follows:

a. Debris slides appear to be the result of streambank erosion removing the toe of naturally steep, unstable slopes. Debris slides are strongly related to geologic material, occurring primarily on massive graywacke and metamorphosed sandstone. Although they are relatively small in size, averaging 8.7 acres, debris slides are quite numerous and actively contribute sediment to channels.

b. Earthflows are much larger than debris slides with an average size of 101.8 acres. However, they are less numerous. They also are highly related to geologic material, occurring almost exclusively on the Franciscan melange of sheared massive sandstone. They appear to be more strongly related to modification of the physical environment by man. Most earthflows occur in grass or oak grass areas and cut-over forests. They do not appear to be as strongly related to streams as debris slides but are more related to faults or shear zones than debris slides.

c. Analysis of undifferentiated landslide characteristics is limited by the small number of occurrences. Consequently, they do not appear to be as significant as debris slides or earthflows in contributing sediment to stream channels.

70. Since mass-wasting events appeared to be strongly related to their proximity to a stream channel and/or geologic materials in the Van Duzen River Basin, a plot of mass-wasting events adjacent to the Van Duzen River was constructed. Additionally, geologic materials underlaying the stream channel were plotted along the longitudinal profile of the Van Duzen River. It appears from Figure 48 that the strong "nick point" at river mile 48.5* may be highly related to the occurrence of a relatively resistant metamorphosed Franciscan sandstone. This nick point appears to interrupt the equilibrium profile of the Van Duzen, causing incision below river mile 48.5. With increased downcutting, streambanks are oversteepened and conditions for mass-wasting of bank material into the channel become more favorable. This is evidenced by the large number of earthflows and debris slides adjacent to the Van Duzen below river mile 48.5 with respect to the lack of these phenomena above the nick point. It may also be noted that introduction of

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* River miles are above the mouth of the Van Duzen River.

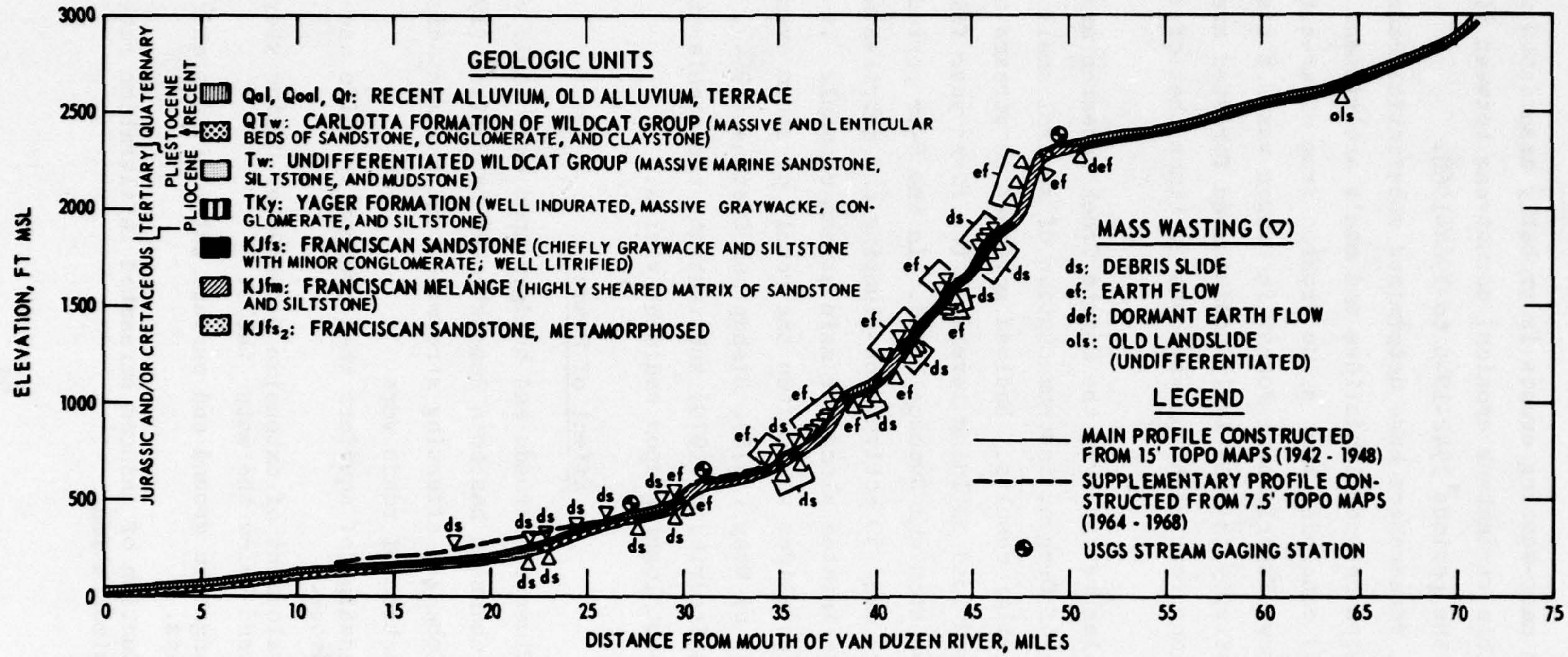

Figure 48. Relationships between geologic materials, mass-wasting events, and longitudinal profiles, Van Duzen River, Calif. (from confluence with Eel River to West Fork)

sediment by these mass-wasting events is probably associated with aggradation (and possible streambank erosion) downstream between river miles 12 and 24 during the periods 1942-1948 to 1964-1968.

71. Several researchers have determined substantial cause and effect relationships between landslides and man's activities. Swanson and Dyrness (1975) concluded that slide erosion from clear-cut areas in the H. J. Andrews Experimental Forest in Oregon was 2.8 times the level of slide activity in relatively undisturbed forested areas. Slide activity along road right-of-ways was 30 times that of forested areas.

72. In similar research at the Coyote Creek research area in the Cascade Mountains of Oregon, instrumentation of several small drainage basins yielded similar results. Bedload movement in streams tripled over prelogging and road building levels in the first year following clear cutting (Swanston and Swanson 1976). In the 5-yr period following clear cutting, over 50 active bank-slumping and debris-avalanching sites have been delineated along the main stream channel. It was also determined that landslides were often the result of storm events. Additional studies by Gray (1970), Bishop and Stevens (1964), Croft and Adams (1950), and Fredriksen (1970) substantiate the acceleration effects of clear-cut logging upon sediment yields.

Effect of Roads

73. The influence of roads and bridges upon hydrologic characteristics of stream channels has been demonstrated by Parizek (1970). Possible adverse changes affecting streamflow and sediment discharge following construction of roads were

- a. Beheading of aquifers when present in soils and shallow bedrock.
- b. Development of extensive groundwater drains where cuts extend below the water table.
- c. Changes in ground and surface water divides and basin areas.
- d. Reduction of induced streambed infiltration rates due to sedimentation.

e. Siltation of channels causing flooding, erosion, and reduction in recharge areas on floodplains.

f. Obstruction of groundwater flow by abutments, retaining walls, and sheet pilings.

g. Changes in runoff and recharge characteristics.

Sediment Study

74. A study to determine sources of sediment and their relationship to certain land use practices in the Eel and Mad River basins was conducted in 1970 (USDA 1970). The USDA River Basin Planning Staff accomplished an in-depth analysis of sediment discharge characteristics for the two basins. This comprehensive analysis of the impact of man's activities upon sediment production in the Eel River and Mad River basins represents an illuminating investigation of the relative importance of man-induced factors versus natural factors. Four types of sediment in terms of source were studied. They included sediment due to streambank, landslide, and sheet and gully erosion, and sediment produced by roads and their construction (Table 4). Results of the investigation are stated in the following six paragraphs and in Tables 4-8.

75. Sediment from streambank erosion was determined to be the largest single contributor to total sediment yield, comprising 64.3 percent. Direct and indirect effects of land use practices upon streambank erosion were not investigated; however, several suggested practices thought to be relevant were logging, road construction, and overgrazing. Streambank erosion sediment was determined for streams of various orders (Table 5). Streams of the second and third order, due to their large number, and the seventh order, due to its large size, appear to be the most significant sediment producers. The authors state that "most of the streambank erosion appears to be a natural occurrence, but some of it has been accelerated by man's activities" (USDA 1970).

76. The production of sediment by landslides of various types accounts for 25.6 percent of the total sediment discharge in the Eel River Basin. Variations in landslide sediment for hydrologic subunits

Table 4

Total Sediment Yield, Acre-Feet Per Year*

Eel River Basin

Subbasin	Streambanks	Landslides	Sheet and Gully	Roads	Total
Outlet Creek-Pillsbury	464	188	360	19	1,031
Middle Fork	1,026	366	225	16	1,633
South Fork	715	621	182	15	1,533
Van Duzen	753	474	108	6	1,341
Main Eel**	4,996	1,517	299	11	6,823
Total	7,954	3,166	1,174	67	12,361
Percent	64.3	25.6	9.5	0.6	100.0

* From USDA (1970).

** Includes Eureka Plain area, which does not actually drain into the Eel River.

Table 5

Streambank Erosion Sediment by Stream Order*

Eel River Basin

Unit	Sediment Yield, Acre-Feet Per Year						
	2nd	3rd	4th	5th	6th	7th	Total
Outlet Creek-Pillsbury	160	189	42	19	54	----	464
Middle Fork	501	298	101	71	55	----	1026
South Fork	296	118	64	64	173	----	715
Van Duzen	278	150	33	276	16	----	753
Main Eel	1344	638	185	83	34	2712	4996
Total	2579	1393	425	513	332	2712	7954

* From USDA (1970).

were determined with explanations of variations given in terms of differences in physical characteristics (climate, topography, geology) (Table 6). An attempt was made to determine causes of slides. Causes determined were generally those associated with streambank erosion. It was concluded that 16 percent of sediment yield attributed to landslides originated from those influenced by man's activities.

77. Sheet and gully erosion was determined to be the source of 9.5 percent of total sediment. Present sediment yields by cause were calculated for each hydrologic subunit. Natural causes accounted for the largest single contributor, amounting to 45.4 percent of total yield (Table 7). Grazing was second with 26.1 percent, followed by deer (15.2 percent), logging (10.9 percent), burning (1.7 percent), and temporary roads (0.7 percent). When the relative significance of these factors is considered by calculating yields per square mile, a somewhat different hierarchy of causes is established. Natural causes remain most significant with a value of 0.70 acre-ft per square mile per year, followed by logging (0.36), burning (0.35), grazing (0.32), and deer (0.05). Sediment yields per square mile for temporary roads were not calculated.

78. Sediment yield from roads accounted for the smallest portion of sediment, less than 1 percent (0.55). This type of sediment yield was defined as that directly caused by road construction and maintenance and includes small landslides within the road prism. Although sediment from roads consists of only a relatively small portion of the total, yield per square mile is quite high. Annual sediment yield by road classification is given for each hydrologic subunit (Table 8).

79. The portion of the total sediment yield due to man's activities is shown in Table 9. Approximately 2316 acre-ft per year (19 percent) is attributed to this source. The value of 1272 acre-ft per year for man-induced streambank erosion is an estimate assuming that 16 percent of the sediment yield for this category was attributed to man's activities. This assumed percentage rate is the same as that for land-slides, which in many cases are related to bank erosion. The relative magnitude of these sediment yield values becomes apparent when they are compared with other sediment yield data. The total sediment yield of the

Table 6

Landslide Erosion Sediment*

Eel River Basin

Unit	Area Square Miles	Sediment Yield Acre-Feet Per Year
Outlet Creek-Pillsbury	709	188
Middle Fork	753	366
South Fork	690	621
Van Duzen	429	474
Main Eel	1324	1517
Total	3905	3166

* From USDA (1970).

Table 7

Sheet and Gully Erosion Sediment by Cause*

Eel River Basin

Unit	Sediment Yield, Acre-Feet Per Year						
	Logging	Burning	Grazing	Roads	Deer	Natural	Total
Outlet Creek-Pillsbury	15	7	43	2	79	214	360
Middle Fork	29	8	57	4	37	90	225
South Fork	43	3	56	T**	28	52	182
Van Duzen	21	1	43	1	9	33	108
Main Eel	22	1	113	1	29	133	299
Total	130	20	312	8	182	522	1174
Percent	11.0	1.7	26.6	0.7	15.5	44.5	100
Acre-ft/sq mi/year	0.36	0.35	0.32	†	0.05	0.70	1.78

* From USDA (1970).
** T = trace.
† Not computed.

Table 8

Sediment from Roads by Type*

Eel River Basin

Unit	Sediment Yield, Acre-Feet Per Year				
	Heavy Duty	Medium Duty	Light Duty	Unimproved	Totals
Outlet Creek-Pillsbury	T**	2	7	10	19
Middle Fork	--	2	6	8	16
South Fork	--	4	5	6	15
Van Duzen	--	2	3	1	6
Main Eel	T**	T**	7	4	11
Total	T**	10	28	29	67

* From USDA (1970).

** T = trace.

Table 9

Influence of Man's Activities on Total Sediment Yield

Cause	Sediment Yield, Acre-Feet Per Year				
	Sheet and Gully Erosion	Landslides	Streambank Erosion	Roads	Totals
Natural	704	2659	6682	-	10,045
Man's Activities	470	507	1272	67	2,316
Total	1174	3166	7954	67	12,361

Eel River Basin recalculated in terms of short tons per square kilometre per year is approximately 2868. The average sediment yield value for North American rivers is 245 short tons per square kilometre per year (Holeman, 1968). The portion of the sediment yield in the Eel River Basin attributed to man's activities, 545 short tons per square kilometres per year, is over twice as large as the average value for North American river basins.

Discussion

80. The morphological changes occurring in the delta and identified from historical, geomorphic analysis indicated that the channels in the delta are adjusting to increased sediment loads. This part of this report has described the sources of sediment and the magnitude of the denudation occurring in the basin. The important question to be discussed is the significance and cause of these high sediment yields. There are four interrelated considerations, which bear on this question: (a) constancy of the denudation rate, (b) accuracy of the man-induced sediment yields, (c) meteorological effects, and (d) dynamic equilibrium.

81. The first consideration pertains to the geological significance of the denudation rate of 12,361 acre-ft per year. This value represents an average denudation rate of 0.0053 ft per year. If this rate was relatively constant in the geologic past, the basin has experienced approximately 53 ft of lowering since the end of Pleistocene time. If the rate remains constant in the future, the Eel River Basin would be nearly reduced to sea level during the next one-half million years. Such an extremely high denudation seems unlikely. Of course, the absolute change in the basin elevation would also be a function of the magnitude of vertical crustal movements in the area. Such extrapolations relating land reduction or lowering to erosion are probably quantitatively inaccurate and do not adequately describe the complexities of these processes. However, these extrapolation do give insight into the relative magnitude of the erosion processes.

82. The second consideration is the significance and the relative accuracy of the sediment yields resulting from man's activities; specifically, whether this amount of sediment could cause the observed geomorphic changes. The relative magnitude of the man-induced sediment yield (19 percent) is an approximation; the actual value could be either higher or lower. The comparison of the relative magnitude of man-induced sediment yield with the magnitude of observed geomorphic change indicates that the man-induced sediment yield may be causing the geomorphic changes. Note that the channel area in the delta has increased by 23 percent.

83. The third consideration is the significance of climate, particularly meteorological change. One could postulate that the basin has experienced atypical meteorological events during the last several decades, which represent a deviation from the regional climatic pattern, and that this deviation has triggered the geomorphic changes. However, insufficient meteorologic data are available to determine conclusively whether or not such a deviation has occurred. One must also distinguish between the extreme meteorologic event versus the extreme flood event. That is, land use may be such that a relatively high-frequency, low-intensity meteorological event could produce a low frequency or large flood.

84. The fourth consideration pertains to the state of dynamic equilibrium in the basin. Certain intrinsic and independent geomorphic conditions may be operating in the basin and are causing or contributing to high flows and sediment yields that, in turn, are producing the geomorphic changes in the delta. Basically, state of dynamic equilibrium is the interaction of the variables, which have been discussed previously, in such a manner as to produce disequilibrium conditions in the basin. Furthermore, dynamic equilibrium is a complex, theoretical factor that should be considered in the evaluation of fluvial phenomena but usually cannot be adequately evaluated itself.

85. The authors believe that the measured sediment yield in the basin is atypically high and cannot be considered an average or constant value. Even though the basin is definitely erosion susceptible, the

long-term average natural sediment yield is probably much lower than 10,045 acre-ft per year. If the long-term average sediment yield is actually lower than the measured value, the difference in the amount must be due to either climatic fluctuation or man's activities, or both. Climatic fluctuation is not a particularly viable solution because such a fluctuation should merely result in changes in meander configuration, and not the dramatic geomorphic changes that were measured. The sediment yield attributed to man's activities, 2316 acre-ft per year, could be the sole cause of the geomorphic changes; however, this solution by itself does not hold particularly well with the belief that the measured natural sediment yield is atypical. Perhaps the man-induced sediment yield is actually much higher than measured; if this were the case, the observed geomorphic changes could easily be explained. Possibly, the best explanation incorporates the underestimation of man-induced sediment yield and the influence of somewhat higher than average rainfall over the last few years.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

General

86. The phenomenon of streambank erosion occurring in the Eel River delta is an informative example of the complex environmental relationships that must be considered and analyzed in order to properly design bank protection or other hydraulic structures. These relationships involve principles and concepts from the fields of geology, hydrology, soil mechanics, and hydraulic engineering. Although the design must be based primarily upon specific local parameters and conditions, it must also take into consideration the reasons why these conditions prevail, as well as any projected, continuing trends or deviations from these conditions. The reasons or causes of erosion may be operating locally near the site or stretch of concern or may be occurring at great distances from the site. Thus, bank erosion studies often may need to address conditions basin-wide.

87. In a broad sense, streambank erosion is a geologic phenomenon. Specifically, it is a geomorphic phenomenon because of the landform modification resulting from changes in the bank line. The examination of the effects of streambank erosion from a geological standpoint permits the effects and conditions to be evaluated in terms of primary causes. The primary causes of bank erosion may be far removed from the observed fact that the critical tractive force has been exceeded at a particular point along a streambank, for example. Geomorphic concepts and techniques, particularly those which lend themselves to quantitative or semiquantitative analysis, may be used to explain why these critical forces have been exceeded. Also, these concepts and techniques may be used to determine whether or not the bank erosion conforms with respect to magnitude, extent, and temporal relationships to the natural, local, and regional geological environment of the area or is atypical and, therefore, possibly caused or triggered by certain nongeological agents such as man's activities. The determination that a site or stretch is being affected by nongeological agents or activities and the extent of

these effects should be important considerations, especially with respect to the development of stream basin master plans.

Conclusions

88. The examination of local conditions at the two demonstration sites and elsewhere in the delta area revealed that upper bank current scour was the type of bank erosion operating in the area.

89. Studies of historic changes in the longitudinal profiles of the Eel and Van Duzen Rivers indicated that the channels have aggraded. Studies of historic changes in bank lines of the Eel River in the lower delta indicated that there has been an increase in bank-to-bank channel area. These historical studies suggest that the erosion mechanism operating in the delta is channel widening and the hydraulic-geomorphic variable most strongly influencing bank erosion is sediment load. Sediment load is, therefore, a basic cause of bank erosion and apparently has increased over the last few decades.

90. The increased sediment loads are not due to any conditions or activities that occur or are in operation in the delta, but they result from conditions in the sediment source area lying upstream and beyond the delta.

91. A review of previously published information indicated that the Eel River drainage basin beyond the delta area possesses natural characteristics that are conducive to high sediment yields. These natural characteristics are: (a) steep, mountainous slopes, (b) landslide-susceptible soils and rock formations, and (c) seasonally severe climate.

92. The natural erosion susceptibility has been increased by logging, over grazing, and road construction. Such activities are estimated to produce approximately 19 percent of the total sediment yield, and possibly more.

Recommendations

93. The design of streambank protection structures or other structures that control or influence fluvial behavior should consider the

natural physical environment of the site or reach in question and also the upstream or downstream of the subject site or reach. This consideration often needs not be as detailed as this study, but some attempt should be made to trace the origin of actual or potential problems to possible or probable sources. Conceivably, problem sources can originate anywhere, upstream or downstream of the subject sites.

94. The determination of probable sources or causes of the problem of bank erosion cannot be made without due consideration to the historical development of the problem in time. The utilization of historical documents, such as maps and aerial photographs, and the extraction and analysis of numerical data taken from these documents can indicate important trends that bear on the design of control structures and should be an integral part of design investigations.

95. The analysis of causes of bank erosion should consider the possible effects of man's activities. In the case of the Eel River Basin, land use practices are contributing to high sediment yields that, in turn, are contributing to channel widening and bank erosion in the delta. In other regions, man's activities are contributing to other responses, which also may result in bank erosion.

96. The geologic and geomorphic investigation of causes of streambank erosion at particular sites or reaches should include the following specific elements:

a. Determination of erosion characteristics. In cooperation with the hydraulic and geotechnical engineer, the investigator should determine the ASCE (American Society of Civil Engineers) erosion type (or types), which are or may be applicable to the subject site.

b. Erosion mechanisms. Probably the most important element is the determination of the mechanism that is producing the erosion. The possible mechanisms are channel deepening, channel widening, and sinuosity changes.

c. Hydraulic-geomorphic variables. This element consists of determining which hydraulic-geomorphic relationship best describes the erosion mechanism.

d. Geomorphic synthesis. The last element consists of identifying those factors or activities that may be affecting the controlling hydraulic-geomorphic relationship. This part of the study should include analysis of both site and nonsite factors.

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In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Smith, Lawson M
Engineering geology and geomorphology of streambank erosion; Report 1: Eel River Basin, California / by Lawson M. Smith and David M. Patrick. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1979.
80 p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; GL-79-7, Report 1)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Section 32 Program, Task II, Work Unit 4.
References: p. 79-80.

1. Bank erosion. 2. Eel River. 3. Engineering geology. 4. Geomorphology. I. Patrick, David M., joint author. II. United States. Army. Corps of Engineers. III. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; GL-79-7, Report 1.
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